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Engenharia

Performance of Management Solutions and Cooperation Approaches for Vehicular Delay-Tolerant Networks

João Alfredo Fazendeiro Fernandes Dias

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Orientador: Prof. Doutor Joel José Puga Coelho Rodrigues

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Dedication

To my family.
For all their love, support, and encouragement.

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Foreword

This thesis describes the research work performed in the scope of the 4-year doctoral research programme and presents its main contributions and achievements. This doctoral programme and inherent research activities were carried out at the Next Generation Networks and Applications Group (NetGNA) research group of the *Departamento de Informática*, University of Beira Interior, Covilhã, Portugal and *Instituto de Telecomunicações*, Covilhã Delegation, Portugal. The research work was supervised by Prof. Dr. Joel José Puga Coelho Rodrigues, and financially supported by the National Funding from the *Fundação para a Ciência e a Tecnologia* (FCT) through the UID/EEA/500008/2013 Project and the grant contract SFRH/BD/86444/2012.

List of Publications

Articles included in the thesis resulting from this 4-year doctoral research programme

Published, accepted or submitted for publication in international journals

- 1. Cooperation advances on vehicular communications: A survey**
João A. F. F. Dias, Joel J. P. C. Rodrigues, and Liang Zhou
Elsevier Vehicular Communications, Vol. 1, No. 1, pp. 22-32, January 2014.
DOI: [dx.doi.org/10.1016/j.vehcom.2013.11.003](https://doi.org/10.1016/j.vehcom.2013.11.003)
- 2. The Impact of Cooperative Nodes on the Performance of Vehicular Delay-Tolerant Networks**
João A. F. F. Dias, Joel J. P. C. Rodrigues, João N. G. Isento, and Jianwei Niu
Mobile Networks and Applications (MONET), Springer US, Vol. 18, No. 6, pp. 867-878, December 2013.
DOI: [dx.doi.org/10.1007/s11036-013-0464-9](https://doi.org/10.1007/s11036-013-0464-9)
- 3. Performance evaluation of cooperative strategies for Vehicular Delay-Tolerant Networks**
João A. F. F. Dias, Joel J.P.C. Rodrigues, and Liang Zhou
European Transactions on Telecommunications, Jonh Wiley and Sons, Vol. 25, No. 8, pp. 815-822, August 2014.
DOI: [dx.doi.org/10.1002/ett.2683](https://doi.org/10.1002/ett.2683)
- 4. Performance evaluation of a cooperative reputation system for vehicular delay-tolerant networks**
João A. F. F. Dias, Joel J. P. C. Rodrigues, Lei Shu, and Sana Ullah
EURASIP Journal on Wireless Communications and Networking, Springer, Vol. 2014, No. 88, pp. 1-13, December 2014.
DOI: [dx.doi.org/10.1186/1687-1499-2014-88](https://doi.org/10.1186/1687-1499-2014-88)
- 5. A Cooperative Watchdog System to Detect Misbehavior Nodes in Vehicular Delay-Tolerant Networks**
João A. F. F. Dias, Joel J. P. C. Rodrigues, Feng Xia, and Constandinos X. Mavromoustakis
IEEE Transactions on Industrial Electronics, Vol. 62, No. 12, pp. 7929-7937, December 2015.
DOI: [dx.doi.org/10.1109/TIE.2015.2425357](https://doi.org/10.1109/TIE.2015.2425357)

6. Cooperation strategies for vehicular delay-tolerant networks

João A. F. F. Dias, Joel J. P. C. Rodrigues, N. Kumar, and K. Saleem
IEEE Communications Magazine, Vol. 53, No. 12, pp. 88-94, December 2015.
DOI: [dx.doi.org/10.1109/MCOM.2015.7355571](https://doi.org/10.1109/MCOM.2015.7355571)

7. Network Management and Monitoring Solutions on Vehicular Communications: A Survey

João A. F. F. Dias, Joel J. P. C. Rodrigues, Kashif Saleem, Neeraj Kumar, Mario L. Proença Jr.
Submitted for publication in an international journal, 2016.

8. REMA: A Resource Management Tool to Improve the Performance of Vehicular Delay-Tolerant Networks

João A. F. F. Dias, Joel J. P. C. Rodrigues, Neeraj Kumar, Valeriy Korotaev, Guangjie Han
Elsevier Vehicular Communications, Vol. 9, pp. 135-143, July 2017.
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Presented and published in the proceedings of international conferences

9. A reputation system to identify and isolate selfish nodes in Vehicular Delay-Tolerant Networks

João A. F. F. Dias, Joel J. P. C. Rodrigues, Lei Shu, and S. Ullah
Proceedings of the 13th International Conference on ITS Telecommunications (IEEE ITST 2013), Tampere, Finland, November 5-7, 2013, pp. 133-138.
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10. A Hybrid System to Stimulate Selfish Nodes to Cooperate in Vehicular Delay-Tolerant Networks

João A. F. F. Dias, Joel J. P. C. Rodrigues, N. Kumar, and Constandinos X. Mavromoustakis
Proceedings of the 2015 IEEE International Conference on Communications (IEEE ICC 2015), London, England, June 8-12, 2015, pp. 5910-5915.
DOI: [dx.doi.org/10.1109/ICC.2015.7249264](https://doi.org/10.1109/ICC.2015.7249264)

11. MoM - A Real Time Monitoring and Management Tool to Improve the Performance of Vehicular Delay Tolerant Networks

João A. F. F. Dias, Joel J. P. C. Rodrigues, Juan F. de Paz, and Juan M. Corchado
Proceedings of the 8th International Conference on Ubiquitous and Future Networks (IEEE ICUFN 2016), Vienna, Austria, July 5-8, 2016, pp. 1071-1076.
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Other publications resulting from this doctoral research programme not included in the thesis

1. **Vehicular Delay-Tolerant Networks – A Novel Solution for Vehicular Communications**
João N. Isento, Joel J.P.C. Rodrigues, João A. F. F. Dias, Maicke C. G. Paula, and Alexey Vinel
IEEE Intelligent Transportation Systems Magazine, Vol. 5, No. 4, pp. 10-19, February 2014.
DOI: [dx.doi.org/10.1109/MITS.2013.2267625](https://doi.org/10.1109/MITS.2013.2267625)

2. **Man4VDTN - A network management solution for vehicular delay-tolerant networks**
Bruno F. Ferreira, Joel J.P.C. Rodrigues, João A. F. F. Dias, and João N. Isento
Elsevier Computer Communications (ComCom), Vol. 39, pp. 3-10, February 2014.
DOI: [dx.doi.org/10.1016/j.comcom.2013.09.007](https://doi.org/10.1016/j.comcom.2013.09.007)

3. **Performance Evaluation of a Real Vehicular Delay-Tolerant Network Testbed**
Maicke C. G. Paula, Joel J.P.C. Rodrigues, João A. F. F. Dias, João N. Isento, and Alexey Vinel
International Journal of Distributed Sensor Networks, Vol. 11, No. 3, pp. 3-10, March 2015.
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Resumo

O vasto número de aplicações e cenários suportados pelas redes veiculares faz com que estas atraiam o interesse não só da comunidade científica, mas também dos governos e da indústria automóvel. A título de exemplo, estas podem ser usadas para a implementação de serviços e aplicações que podem ajudar os condutores dos veículos a tomar decisões nas estradas, para a disseminação de conteúdos publicitários, ou ainda, para permitir que existam comunicações em zonas rurais ou remotas onde não é possível ter uma infraestrutura de rede convencional. Contudo, as propriedades únicas das redes veiculares fazem com que seja necessário ultrapassar um conjunto de desafios que têm grande impacto na sua aplicabilidade.

A maioria dos desafios que as redes veiculares enfrentam advêm da grande mobilidade dos veículos e da topologia de rede que está em constante mutação. Esta situação faz com que este tipo de rede seja suscetível de disrupção, que as oportunidades de contacto sejam escassas e de curta duração, e que a ligação seja intermitente. Fruto destas adversidades, a disseminação dos dados torna-se um tópico de investigação bastante promissor na área das redes veiculares e por esta mesma razão é abordada neste trabalho de investigação. O trabalho descrito nesta tese é motivado pela necessidade de propor novas abordagens para lidar com os problemas inerentes à disseminação dos dados em ambientes veiculares.

Para garantir o sucesso da disseminação dos dados em ambientes veiculares é importante que este tipo de redes garanta a cooperação entre os nós da rede. Contudo, neste tipo de ambientes não é possível garantir um cenário totalmente cooperativo. Este cenário faz com que as redes veiculares sejam suscetíveis à presença de nós não cooperativos que comprometem seriamente o desempenho global da rede. Por outro lado, os nós cooperativos podem ver o seu desempenho comprometido por causa da sobrecarga de serviços que poderão suportar.

Para tentar resolver alguns destes problemas, esta tese apresenta várias propostas e estudos sobre o impacto de estratégias de cooperação, monitorização e gestão de rede no desempenho das redes veiculares com ligações intermitentes (Vehicular Delay-Tolerant Networks - VDTNs). O objetivo das propostas apresentadas nesta tese é melhorar o desempenho global da rede. Em particular, as estratégias de cooperação e gestão de rede são exploradas para melhorar e otimizar o uso dos recursos da rede. Ficou demonstrado que o uso deste tipo de estratégias e metodologias contribui para um aumento significativo do desempenho da rede, não só em termos de agregados de pacotes (“*bundles*”) entregues, mas também na diminuição do volume de recursos desperdiçados.

Os resultados observados neste trabalho procuram contribuir para o avanço do estado da arte em métodos e estratégias que visam ultrapassar alguns dos desafios que advêm das propriedades e desenho conceptual das redes veiculares.

Palavras-chave

Redes Móveis *Ad hoc* (MANET), Redes Veiculares *Ad hoc* (VANET), Redes com Ligações Intermitentes, Redes Veiculares com Ligações Intermitentes, Cooperação, Redes Veiculares, Comunicações Veiculares, Redes Oportunistas, Sistema de Reputação, Nós não cooperativos, Avaliação do Desempenho, Mecanismos de Reputação, Abordagem híbrida, Sistema de Vigia Cooperativo, Monitorização e Gestão de Rede, Gestão de recursos, Simulação, Conectividade Rural e Urbana.

Resumo alargado em Português

Introdução

Esta secção resume, de forma alargada, os 4 anos de trabalho de investigação no âmbito da tese de doutoramento intitulada “*Performance of Management Solutions and Cooperation Approaches for Vehicular Delay-Tolerant Networks*”. Esta tese foca-se no estudo e proposta de estratégias e metodologias de cooperação, monitorização e gestão de rede para ambientes veiculares. Numa primeira fase é descrito o enquadramento da tese, definido o problema abordado e os principais objetivos do estudo. De seguida, a hipótese de investigação é descrita e são apresentadas as principais contribuições deste trabalho para o avanço do estado da arte.

Enquadramento da Tese

Uma rede veicular pode ser definida como uma rede que se auto-organiza, onde os veículos se deslocam ao longo das estradas, comunicando uns com os outros ou com algum tipo de infraestrutura rodoviária. Este tipo de rede permite que as mensagens/informações possam circular pela rede sem necessidade de uma infraestrutura de rede tradicional. Para comunicarem entre si, os veículos estão equipados com dispositivos sem fios de curto alcance. Dada a grande mobilidade dos veículos, a topologia das redes veiculares está em constante mutação, o que se traduz numa rede em que os nós podem estar localizados dentro ou fora do alcance do raio de comunicação uns dos outros [1-3].

Nos últimos anos, este tipo de redes tem vindo a atrair muita atenção, não só da comunidade científica, mas também dos governos e da indústria automóvel. Algumas empresas ou consórcios do ramo automóvel têm no mercado, ou estão a desenvolver, protótipos de automóveis equipados com sensores, computadores de bordo, e dispositivos de comunicação sem fios [4-6]. Com base nesta tendência, é esperado que nos próximos anos as redes veiculares comecem a ter bastante utilidade e a serem usadas em diversos cenários.

Uma das principais razões para o interesse exponencial neste tipo de redes é o elevado número de ambientes, serviços e aplicações que suportam. Alguns destes serviços e aplicações têm um impacto direto na vida diária das pessoas [7]. Por exemplo, as redes veiculares podem ser usadas para melhorar a segurança nas estradas, para otimizar o tráfego rodoviário e a capacidade das vias automóveis, ou ainda para recolher dados de sensores em redes de monitorização. Podem também ser usadas para permitir àqueles que viajam dentro dos veículos possam usufruir de serviços comerciais (ex., publicidade) ou usar aplicações de entretenimento (ex., partilha de conteúdo multimédia). As redes veiculares não se limitam a ser implementadas em cenários urbanos ou em áreas desenvolvidas. Estas também podem ser usadas em ambientes rurais ou em cenários de catástrofe, permitindo a existência de comunicações onde não é possível ter uma infraestrutura convencional de rede/comunicação.

Apesar dos inúmeros cenários em que podem ser aplicadas, as redes veiculares têm ainda de ultrapassar alguns desafios/problemas de cariz tecnológico. Alguns destes desafios são partilhados pelas redes *ad hoc* e sem fios, enquanto outros advêm das propriedades únicas deste tipo

de arquitecturas. A topologia dinâmica e em constante mutação é um destes desafios, se não o maior que as redes veiculares enfrentam. Este está diretamente relacionado com a velocidade e mobilidade dos veículos, que leva a que as oportunidades de contacto ocorram de forma esporádica e de curta duração [1-3, 8]. Para aumentar o impacto negativo deste problema, as redes veiculares têm algumas limitações em termos de raios de transmissão, obstruções de sinal causadas por fatores físicos (ex., edifícios e obstáculos), e interferências (ex., canais de comunicação congestionados pela sobrecarga de utilizadores). Combinando todos estes fatores, facilmente se percebe a razão pela qual as redes veiculares são suscetíveis de disrupção, ligações intermitentes, frequente fragmentação dos dados, resultando numa possível ausência de ligação ponto-a-ponto entre a origem e o destino das mensagens.

Algumas arquitecturas de rede foram já propostas para tentar ultrapassar ou minimizar o impacto de alguns destes problemas. As redes veiculares *ad hoc* (*Vehicular Ad Hoc Networks* - VANETs) [9, 10] exploram os veículos como nós móveis, expondo-os às regras e condições de tráfego. Neste tipo de arquitectura, os veículos podem interagir uns com os outros ou com algum tipo de infraestrutura colocada na berma das estradas. Seguindo esta abordagem, as VANETs consideram três tipos de metodologias para permitir a comunicação entre os nós da rede [11-13]: Veículo-para-Veículo (V2V), Veículo-para-Infraestrutura (V2I), e uma abordagem híbrida combinando as duas anteriores. Todas as comunicações assumem a existência de uma ligação ponto-a-ponto. Esta abordagem faz com que as VANETs sejam suscetíveis a longos tempos de espera, à fragmentação da rede, e à desconexão.

A arquitectura das redes com ligações intermitentes, ditas *Delay-Tolerant Networks* (DTNs) [14-17] procura melhorar a fiabilidade da rede através do suporte de comunicações intermitentes entre os nós da rede. Esta arquitectura coloca a camada de “agregação” (“*bundle layer*”) por baixo da camada de “aplicação”, permitindo implementar um paradigma de comutação assíncrona de agregados de pacotes (“*bundles*”). Este paradigma explora a grande mobilidade dos nós móveis para construir uma sessão extremo-a-extremo para a transferência de dados.

Seguindo a abordagem proposta pelas DTNs e aproveitando alguns contributos de outras tecnologias, as redes veiculares com ligações intermitentes (*Vehicular Delay-Tolerant Networks* - VDTNs) [18, 19] implementam uma sinalização fora de banda com a separação do plano de controlo (“*control plane*”) e o plano de dados (“*data plane*”). O plano de controlo é usado para trocar mensagens de sinalização que, para além de outras tarefas, permitem reservar recursos para serem usados no plano de dados. Já o plano de dados é usado para o envio de “*bundles*” e para realizar algumas tarefas de gestão de “*buffers*”. Ao contrário das DTNs, as VDTNs implementam a camada de “agregação” sob a camada de “rede”, permitindo o encaminhamento de “*bundles*”, os datagramas IP (*Internet Protocol*). Esta arquitectura considera três tipos de nós: terminais, nós fixos de retransmissão, e móveis. Os nós terminais são responsáveis pela criação e recepção final de dados. Os nós de retransmissão possuem grande capacidade de armazenamento, e normalmente são colocados nas principais interseções do cenário físico. Este tipo de nó tem como principal objetivo aumentar o número de oportunidades de contacto entre os nós, resultando num aumento da probabilidade de entrega dos dados [20]. Por último, os nós móveis movimentam-se ao longo das estradas, trocando “*bundles*” entre si, mas também com os outros tipos de nós com o intuito de os entregar ao seu destino final, podendo também ser responsáveis pela criação e recepção final de dados.

Resumo alargado em Português

Apesar dos avanços já alcançados nos últimos anos através dos estudos realizados nas arquiteturas acima apresentadas, as redes veiculares ainda enfrentam alguns desafios que têm de ser ultrapassados. Estes desafios incluem a gestão de recursos (ex., energia, armazenamento) e a comunicação cooperativa entre os nós da rede (ex., encaminhamento, disseminação dos dados). Estes campos de investigação são importantes e desafiantes dada a sua complexidade de implementação. Por esta razão, a investigação realizada no âmbito deste programa de doutoramento foca-se nos problemas inerentes das comunicações cooperativas e das funcionalidades de gestão e monitorização das redes veiculares. Estes problemas serão estudados através da implementação e avaliação de desempenho de metodologias de cooperação, gestão e monitorização de rede, considerando a arquitetura VDTN.

Descrição do Problema e Objetivos de Investigação

Esta tese aborda não só a problemática da cooperação entre nós, mas também como a arquitetura VDTN pode implementar estratégias de monitorização e gestão de rede, com o intuito de melhorar o seu desempenho global. A importância destes dois tópicos advém da exigência que o aumento da complexidade das redes veiculares trouxe, exigindo que sejam criadas ferramentas e estratégias mais sofisticadas. Nas VDTN, a cooperação tenta ultrapassar a possível inexistência de uma ligação extremo-a-extremo, entre a origem e destino dos dados, através da partilha de recursos por parte dos nós da rede. Por sua vez, a gestão e monitorização da rede procura manter uma visão clara do estado da rede, abordando e corrigindo problemas à medida que estes vão surgindo.

No que diz respeito à cooperação, a maioria dos estudos já publicados concluiu que a cooperação entre os nós, nas redes veiculares, contribui para uma melhoria significativa do desempenho global da rede. Contudo, os mesmos estudos mostram que implementar estratégias de cooperação nas comunicações veiculares não é uma tarefa fácil, e coloca um número considerável de desafios. Desta forma, é muito importante estudar a melhor forma de estimular os nós a cooperar entre si, evitando que possam divergir do protocolo. Nós com um comportamento divergente têm um impacto bastante negativo na rede e comprometem seriamente a sua eficiência. A título de exemplo, um nó pode ter um comportamento divergente e não estar disponível para cooperar uma vez que não obtém nenhuma vantagem em partilhar os seus recursos com outros. Por outro lado, transportar “*bundles*” de outros obriga a que os nós tenham de partilhar o seu espaço de armazenamento. Outro exemplo deste tipo de nós, é um nó com bastante mobilidade na estrada (ex., táxis, automóveis ou autocarros). Este tipo de veículo tem uma grande probabilidade de ser escolhido para enviar “*bundles*” de outros, sujeitando-os à sobrecarga de serviços de outros nós. Isto faz com que estes nós consumam rapidamente os seus recursos, forçando-os a divergir do protocolo de modo a evitar o comprometimento dos seus dados e recursos. Para evitar que tal comportamento ocorra, várias abordagens podem ser tidas em conta. Uma possível abordagem é a utilização de mecanismos de cooperação para ajudar os protocolos de encaminhamento e estratégias de disseminação de dados a escolher o melhor caminho entre a origem e o destino dos dados. Outra solução possível é estimular os nós a cooperar oferecendo-lhes incentivos e punindo aqueles que não têm um comportamento cooperativo.

Apesar da melhoria trazida pelas estratégias de cooperação no que diz respeito ao desempenho da rede, outras abordagens podem ser consideradas. Normalmente, este tipo de redes

tem vários constrangimentos no que diz respeito a recursos (ex., energia e armazenamento). É essencial desenvolver estratégias que utilizem funcionalidades de monitorização e gestão da rede para prevenir, detetar, e resolver anomalias na rede, permitindo otimizar o consumo de recursos. Se um nó tem constrangimentos de energia ou armazenamento, é importante detetar esta situação o quanto antes e avisar os restantes nós, para que evitem comunicar com este. O envio de “*bundles*” para nós com constrangimentos pode comprometer seriamente a probabilidade de estes chegarem ao seu destino, uma vez que os nós que as transportam podem ficar sem energia para continuar a ser parte integrante da rede, ou podem ter de as apagar para terem espaço suficiente para continuar a executar funcionalidades da rede. Uma possível solução para este problema, e que pode ajudar a minimizar o impacto que a limitação de recursos tem na rede, é criar ferramentas de monitorização capazes de recolher dados em tempo real relativos ao desempenho dos nós da rede. Este tipo de ferramentas permite ainda que os administradores da rede possam detetar e desenvolver medidas para resolver constrangimentos na rede.

A qualidade de serviço pode também ser garantida (ou melhorada) pelas estratégias de gestão da rede. A mobilidade e a natureza *ad hoc* dos ambientes veiculares não permitem a adoção de estratégias de alocação de recursos usadas nas redes tradicionais. Nas redes veiculares estas funções são normalmente executadas pelos protocolos de encaminhamento que são desenhados para serem responsáveis pela gestão da rede. Contudo, outras metodologias podem ser desenvolvidas para realizarem funcionalidades de gestão e monitorização da rede com o intuito de otimizar os parâmetros dos protocolos de encaminhamento. Esta abordagem pode levar a topologias mais estáveis e a uma menor sobrecarga na rede, aumentando o volume de “*bundles*” entregues e diminuindo o consumo de recursos.

Estas observações motivam a proposta e criação de novas soluções de cooperação, monitorização e gestão de redes veiculares. Desta forma, o principal objetivo desta tese passa por apresentar propostas de cooperação, monitorização e gestão de rede para a arquitectura VDTN. Além disso, estudos de avaliação de desempenho são necessários para aferir a viabilidade destas novas propostas. Para atingir o objetivo principal desta tese, vários objetivos intermédios foram identificados:

- Revisão do estado da arte das arquitecturas para redes veiculares e com ligações intermitentes, dos seus serviços e aplicações, assim como das estratégias de cooperação, monitorização e gestão de rede já existentes;
- Construção e avaliação de desempenho de um sistema de reputação para a arquitectura VDTN, que será considerado para identificar e detetar a presença de nós não cooperativos, responsáveis pela degradação do desempenho da rede;
- Proposta e avaliação de desempenho de um sistema híbrido que implementa vários mecanismos de incentivo, cujo objetivo é encorajar nós não cooperativos a partilharem os seus recursos em benefício da melhoria do desempenho da rede;
- Desenvolvimento e avaliação de desempenho de um sistema de vigia cooperativo para detetar nós que divergem do protocolo e reduzir o seu impacto negativo na arquitectura VDTN;
- Construção e desenvolvimento de uma ferramenta de monitorização de rede capaz de lidar com anomalias e constrangimentos na rede VDTN;

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- Proposta e avaliação do desempenho de uma ferramenta de gestão de recursos para a arquitectura VDTN, que procura minimizar o consumo de recursos na rede e ajudar os protocolos de encaminhamento na escolha do melhor “caminho” entre a origem e destino dos “bundles”.

Hipótese de investigação

Esta tese propõe um conjunto de novas abordagens focadas na cooperação, monitorização e gestão de rede com o intuito de melhorar o desempenho das redes veiculares com ligações intermitentes (VDTNs). O argumento apresentado nesta tese é o seguinte:

O desempenho das VDTNs depende da cooperação entre os nós e como estes consomem os recursos da rede. O nível de cooperação de cada nó da rede pode ser medido através da percentagem de recursos que estes partilham com os outros. Os recursos partilhados podem incluir a cedência de espaço de armazenamento para guardar “bundles” provenientes de outros nós, ou passar parte do tempo de contacto a enviar estes mesmos “bundles” com o intuito de os fazer chegar ao seu destino. Os nós devem ainda evitar contactos com nós divergentes com o intuito de aumentar a probabilidade de entrega dos “bundles” e diminuir o consumo de recursos na rede. Este consumo pode ainda ser atenuado através da monitorização constante da rede e da implementação de mecanismos de encaminhamento direccionados para a optimização do desempenho da rede.

De forma a sustentar este argumento, foi utilizada a seguinte abordagem:

Em primeiro lugar foi estudado o progresso das tecnologias, serviços e aplicações das redes veiculares. Através deste estudo as principais arquitecturas foram identificadas, bem como as suas principais limitações e desafios. De seguida, foram revistas e estudadas de forma detalhada as principais estratégias de cooperação e gestão da rede já existentes, identificando as suas limitações, desafios, e pontos de investigação ainda em aberto.

Relativamente ao tópico da cooperação, a tese começa por propor e estudar dois níveis de cooperação na arquitectura VDTN. O primeiro nível considera a cooperação ao nível do “buffer” onde os nós são forçados a ceder uma percentagem da sua capacidade de armazenamento para guardar “bundles” provenientes de outros nós. Já o segundo nível de cooperação concretiza a cooperação ao nível do plano de dados, forçando os nós a enviar “bundles” de outros durante uma percentagem do tempo total do contacto. Contudo, não é possível assumir a existência de um cenário totalmente cooperativo, pelo que são propostos três sistemas (i.e., reputação, híbrido e vigia) que lidam com a presença de nós não cooperativos e divergentes. Todos estes sistemas usam uma estratégia de reputação para detetar, identificar e classificar os nós quanto ao seu comportamento cooperativo. Enquanto os sistemas de reputação e vigia excluem imediatamente nós não cooperativos, o sistema híbrido procura incentivá-los a cooperar antes de os excluir definitivamente. Foram realizados diversos estudos para avaliação de desempenho destas estratégias e sistemas de cooperação na arquitectura VDTN. Os resultados obtidos são usados para demonstrar a viabilidade e vantagens das novas estratégias de cooperação.

As metodologias de gestão e monitorização da rede são sugeridas com o objetivo de assistir os protocolos de encaminhamento e as ferramentas de administração a melhorar o desempe-

nho da rede. Neste sentido, duas ferramentas foram propostas. A primeira, é uma ferramenta de monitorização que recolhe dados em tempo real acerca do desempenho e estado dos nós na rede, procurando anomalias e possíveis constrangimentos na rede. A segunda, é uma ferramenta que lida com constrangimentos de recursos (ex., armazenamento) da rede. Foram realizadas diversas análises para avaliar o impacto destas ferramentas e monitorização de rede nas VDTNs. Os resultados obtidos são usados para demonstrar a viabilidade e as vantagens das novas estratégias de gestão e monitorização de rede.

Principais contribuições

A primeira contribuição desta tese é uma análise detalhada do estado da arte das estratégias de cooperação já existentes para redes veiculares e com ligações intermitentes. Esta contribuição está descrita com detalhe no Capítulo 2, que consiste num artigo publicado no número inaugural da revista *“Vehicular Communications”* da Elsevier [21]. Este estudo recebeu, em 2016, uma menção honrosa como um dos artigos mais citados desde 2011.

A segunda contribuição é a proposta e a concretização de dois níveis de cooperação para as VDTNs tendo em conta a sinalização fora de banda com a separação do plano de controlo e de dados característica das VDTNs. Este estudo está descrito, em detalhe, no Capítulo 3, e consiste num artigo publicado na revista *“Mobile Networks and Applications”* (MONET) da Springer, num número especial intitulado *“Network Protocols and Algorithms for Vehicular Ad Hoc Networks”* [22].

A terceira contribuição desta tese é apresentada no Capítulo 4 e descreve a proposta de quatro estratégias de cooperação para fomentar a cooperação entre os nós da rede. A descrição e validação desta proposta foi publicada na revista *“European Transactions on Telecommunications”*, da John Wiley and Sons [23].

A quarta contribuição é a criação, construção e validação de um sistema de reputação para detetar, identificar e isolar nós com um comportamento não cooperativo. Este estudo é descrito em detalhe no Capítulo 5. Uma versão preliminar deste trabalho, descrita no Anexo 1, foi apresentada na 13ª edição da *“International Conference on ITS Telecommunications”* (ITST 2013) [24]. A versão completa deste estudo foi publicada na revista *“EURASIP Journal on Wireless Communications and Networking”* da Springer [25].

A quinta contribuição, apresentada no Anexo 2, é a proposta e a criação de duas estratégias para encorajar nós não cooperativos a partilhar os seus recursos em benefício da rede. Para avaliar o impacto destas estratégias na arquitectura VDTN, foi desenvolvido um sistema híbrido adaptando o sistema de reputação proposto em [25]. Esta contribuição foi apresentada na edição de 2015 da *“Internacional Conference on Communications”* (IEEE ICC 2015) organizada pela IEEE Communications Society [26].

A sexta contribuição foi publicada num *“Special Section on Connected Vehicles - Advancements in Vehicular Technologies and Informatics”* conjunto das revistas *“IEEE Transactions on Industrial Electronics”* e *“IEEE Transactions on Industrial Informatics”* [27], e é descrita em detalhe no Capítulo 6. Esta contribuição apresenta a proposta e construção de um sistema de vigia cooperativo que permite aos nós da rede detetar, classificar e agir contra nós não coope-

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rativos.

A sétima contribuição, descrita no Capítulo 7, analisa a influência das estratégias de cooperação propostas para a arquitectura VDTN. Este trabalho procura também servir de tutorial sobre como desenvolver estratégias de cooperação para as redes veiculares com ligações intermitentes (redes VDTN). É feita uma revisão do tópico onde são apresentados os seus desafios e motivações. Este estudo foi publicado na revista “*IEEE Communications Magazine*” [28].

A oitava contribuição desta tese é uma revisão detalhada do estado da arte das estratégias de gestão e monitorização da rede para ambientes veiculares. Esta contribuição é apresentada no Capítulo 8 e foi submetida para publicação numa revista internacional.

A nona contribuição é descrita e analisada em detalhe no Anexo 3. Esta contribuição consiste na proposta e avaliação de desempenho de uma ferramenta de monitorização capaz de recolher informação em tempo real não só do desempenho da rede, mas também de cada um dos nós que fazem parte dela. Esta contribuição foi apresentada na 8ª edição da “*International Conference on Ubiquitous and Future Networks*” (ICUFN 2016) [29].

A décima contribuição apresenta a proposta e validação de um mecanismo de gestão de recursos para lidar com constrangimentos relacionados com o armazenamento e energia dos nós. Esta contribuição é descrita no Capítulo 9 e foi publicada na revista “*Vehicular Communications*” da Elsevier [30].

Por fim, a última contribuição desta tese, é a criação de dois módulos (cooperação e gestão de rede) para o simulador VDTNSim [31] (disponível para download em <http://vdtntsim.it.ubi.pt>), permitindo que seja possível avaliar o desempenho de políticas direcionadas para lidar com nós que divergem do protocolo, seja por um comportamento malicioso ou por algum tipo de constrangimento.

Principais Conclusões

Ao longo da presente tese foi estudado e avaliado o desempenho de redes veiculares com ligações intermitentes (redes VDTN) através da aplicação de estratégias de cooperação, monitorização e gestão da rede. Este ponto apresenta um resumo do trabalho realizado e aponta algumas sugestões que podem ser seguidas como linhas de orientação para futuras investigações neste tópico.

Após a apresentação e delimitação do tema da tese, onde foram identificados os principais desafios e problemas que as redes veiculares enfrentam, foram descritos os objetivos e apresentadas as suas principais contribuições. De seguida, os principais aspetos da cooperação nas redes veiculares e com ligações intermitentes foram descritos no Capítulo 2. Este capítulo começou por identificar e fazer uma revisão dos principais serviços e aplicações para redes veiculares *ad hoc*, que permitiu não só a identificação dos seus contextos de aplicação e das principais estratégias de cooperação, mas também das suas principais limitações que motivaram a introdução de novos paradigmas. Um destes paradigmas levou ao aparecimento das redes com ligações intermitentes (DTNS e VDTNs) que baseiam a sua operação numa abordagem de

“armazenamento, transporte e envio de *“bundles”*. Ambas as arquitecturas foram descritas em detalhe enumerando as suas principais contribuições para o avanço do estado da arte no que diz respeito à cooperação entre nós. Por fim, foram identificados alguns pontos de investigação em aberto que resultaram dos estudos desenvolvidos ao longo desta tese.

Identificados os pontos de estudo desta tese no que diz respeito ao tópico cooperação, nos Capítulos 3 e 4 foram apresentadas as primeiras propostas para concretizar a cooperação entre nós nas redes VDTNs. O Capítulo 3 apresenta a proposta de adaptação da arquitectura VDTN para suportar estratégias de cooperação tanto no plano de controlo como no plano de dados. Desta forma, os nós cooperam uns com os outros não só ao trocarem *“bundles”*, mas também ao partilharem uma percentagem dos seus recursos (ex. armazenamento, tempo de ligação) em prol da melhoria do desempenho da rede. Os resultados deste estudo permitiram identificar abordagens e estratégias cooperativas que não resolvendo totalmente o problema abordado nesta tese, ofereceram mesmo assim alguns contributos conceptuais. No Capítulo 4, e após a realização de dois níveis de cooperação nas VDTNs, foram propostas quatro abordagens para fomentar a cooperação entre os nós. Estas abordagens fazem com que os nós cooperem com uma percentagem dos seus recursos, isto é, a cada oportunidade de contacto os nós têm de partilhar uma percentagem do seu espaço de armazenamento para receber e guardar *“bundles”* provenientes de outros nós. Ao mesmo tempo devem usar uma percentagem do seu tempo de contacto para enviar *“bundles”* de outros. Contudo, a operação de cada uma destas propostas diferencia-se através da forma como a percentagem de recursos a partilhar é calculada. Os resultados deste estudo estão descritos no Capítulo 4 e mostram uma clara melhoria no desempenho da rede quando comparado com uma abordagem que não considera qualquer técnica de cooperação.

Apesar das melhorias observadas no desempenho da rede com as propostas anteriores, estas não foram desenhadas para detetar e agir contra nós que divergem do protocolo. Para isso, foi proposto e construído um sistema de reputação que, a cada oportunidade de contacto, calcula um coeficiente de reputação para cada um dos intervenientes com base no seu desempenho na rede. Esta abordagem permite detetar, identificar e isolar nós não cooperativos para que o seu comportamento negativo não influencie o desempenho dos nós cooperativos. Os resultados obtidos através do estudo apresentado no Capítulo 5 confirmam a afirmação anterior, permitindo ainda verificar que este tipo de abordagem é efetiva e eficaz na melhoria do desempenho da rede. Este sistema de reputação foi adaptado e transformado num sistema híbrido que permite após a identificação e detecção de nós não cooperativos aplicar algumas estratégias de incentivo à cooperação com o intuito de os fazer alterar o seu comportamento. Os estudos realizados através deste sistema híbrido são apresentados e descritos no Anexo 2.

No que diz respeito à cooperação, a última proposta foi apresentada e estudada no Capítulo 6. Neste trabalho, foi proposto um sistema de vigia cooperativo para equipar os nós da rede com uma ferramenta capaz de detectar nós não cooperativos. Para isso, este sistema atribui um coeficiente de cooperação a cada nó da rede, para que a cada oportunidade de contacto este seja atualizado mediante as opiniões de três módulos distintos (classificação, avaliação dos seus vizinhos e decisão). O módulo de classificação categoriza os nós de acordo com uma topologia que se baseia no valor cooperativo observado pelo próprio nó. O módulo de avaliação dos vizinhos calcula o valor cooperativo de um nó com base na opinião dos seus vizinhos. Por fim, o módulo de decisão recolhe informação dos outros módulos para recompensar ou punir os

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nós pelo seu comportamento na rede. Foram efetuados diversos estudos para avaliar o desempenho deste sistema, considerando a probabilidade de entrega de “*bundles*”, o tempo médio de entrega ao destino e o número de “*bundles*” descartados. Estes estudos mostraram uma grande eficácia deste sistema para melhorar o desempenho da rede.

Os avanços obtidos através das estratégias de cooperação propostas (apresentados em forma de tutorial no Capítulo 7) e a procura pela otimização da qualidade de serviço (QoS) nas comunicações entre nós em redes com ligações intermitentes motivaram a criação de metodologias de monitorização e gestão de rede. Para isso, foi necessário efetuar um estudo que permitisse identificar as principais limitações e desafios das redes veiculares e com ligações intermitentes em termos de gestão de rede. Este estudo, descrito em detalhe no Capítulo 8, apresentou as principais contribuições já existentes neste tópico de investigação e identificou alguns pontos em aberto que serviram de base para a proposta de novas estratégias de monitorização e gestão de rede para a arquitectura VDTN.

Fruto do estudo anterior, foram construídas duas ferramentas para lidar com a gestão de recursos nas redes VDTN. A primeira, apresentada e descrita no Anexo 3, opera em tempo real recolhendo dados sobre o desempenho dos nós e da rede com o objetivo de detetar algum tipo de constrangimento. Esta ferramenta não se limita a tarefas de monitorização e tira partido da arquitectura VDTN e da cooperação entre os nós para melhorar o desempenho da rede. Para isso, recolhe relatórios de desempenho dos nós e espalha pela rede medidas que procuram resolver os constrangimentos detetados. Estas medidas podem passar pela exclusão da rede de nós com constrangimentos ao nível dos recursos, ou pelo pedido de alteração de um dado comportamento responsável por deteriorar o desempenho da rede. Para conseguir desempenhar estas funcionalidades, a ferramenta de monitorização baseia a sua operação em três módulos: monitorização, gestão e interface do utilizador. O módulo de monitorização é responsável por processar os relatórios de desempenho provenientes dos nós móveis e por manter atualizada uma tabela de estado com toda a informação relativa a cada nó em execução na rede. O módulo de gestão é responsável por gerar as medidas e os alertas quando um constrangimento é detetado. Por fim, o módulo de interface com o utilizador permite que os administradores de rede possam verificar o estado da rede em monitorização a qualquer momento. Os estudos realizados mostraram um excelente comportamento desta ferramenta na melhoria do desempenho da rede através da diminuição do impacto de nós com constrangimentos, o que levou a um aumento significativo da probabilidade de entrega de “*bundles*”.

Por último, no Capítulo 9 é descrito o desenvolvimento de uma ferramenta, chamada REMA, exclusivamente dedicada à gestão de recursos dos nós. Esta ferramenta foi proposta com o objetivo de ajudar os protocolos de encaminhamento a minimizar o consumo de recursos da rede, através de uma metodologia de encaminhamento sofisticada. Esta metodologia tira partido da arquitectura VDTN, mais concretamente da sinalização fora de banda para introduzir um mecanismo de encaminhamento baseado em dois passos. A cada oportunidade de contacto, os nós enviam para o REMA o seu relatório acerca dos “*bundles*” que transportam, que depois calcula quais destes “*bundles*” devem ser encaminhados para cada um dos nós. Esta decisão é tomada tendo em conta não só os próprios nós e o seu desempenho, mas também o seu próximo destino. O estudo da análise do desempenho desta ferramenta mostra um aumento significativo do desempenho da rede quando consideramos protocolos de encaminhamento que não limitam o número de cópias de cada “*bundle*” na rede.

O objetivo principal desta tese bem como todos os objetivos parciais foram totalmente cumpridos. As estratégias e metodologias de cooperação para redes veiculares com ligações intermitentes permitem potenciar a aplicabilidade deste tipo de redes em vários cenários e contextos de utilização. Devido às propostas apresentadas ao longo desta tese é possível aumentar a probabilidade de entrega dos “bundles” e ainda diminuir o impacto negativo dos nós não cooperativos. Isto permite diminuir não só o número de transmissões na rede, mas também o número de recursos desperdiçados. No que diz respeito à monitorização e gestão da rede foi possível dotar este tipo de arquiteturas veiculares de ferramentas capazes de diminuir significativamente o desperdício de recursos através da diminuição do número de “bundles” que são descartados e do número de cópias de cada “bundle” que são necessários para os entregar com sucesso no seu destino.

Perspectivas de Trabalho Futuro

Para concluir este trabalho de investigação, resta sugerir futuros tópicos de estudo resultantes do trabalho de investigação desenvolvido:

- Propor, construir e avaliar mecanismos que lidem com a topologia dinâmica das redes veiculares com ligações intermitentes e com a grande mobilidade dos veículos.
- Propor, construir e avaliar mecanismos que lidem com a gestão de tráfego em redes veiculares com ligações intermitentes.
- Estudar, implementar e avaliar técnicas e mecanismos de segurança que previnam que os dados sejam corrompidos ou comprometidos, tornado as comunicações entre os nós mais fiáveis e seguras.
- Introduzir o conceito de “cloud networking” na arquitetura VDTN e estudar a sua aplicabilidade através de estudos conduzidos no simulador [31] e na “testbed” laboratorial [32] desenvolvidos para as VDTNs.
- Implementar e avaliar os resultados das propostas apresentadas nesta tese na “testbed” real [33], para sua validação e comparação com os resultados obtidos por simulação.

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Abstract

A wide range of daily-life applications supported by vehicular networks attracted the interest, not only from the research community, but also from governments and the automotive industry. For example, they can be used to enable services that assist drivers on the roads (e.g., road safety, traffic monitoring), to spread commercial and entertainment contents (e.g., publicity), or to enable communications on remote or rural regions where it is not possible to have a common network infrastructure. Nonetheless, the unique properties of vehicular networks raise several challenges that greatly impact the deployment of these networks.

Most of the challenges faced by vehicular networks arise from the highly dynamic network topology, which leads to short and sporadic contact opportunities, disruption, variable node density, and intermittent connectivity. This situation makes data dissemination an interesting research topic within the vehicular networking area, which is addressed by this study. The work described along this thesis is motivated by the need to propose new solutions to deal with data dissemination problems in vehicular networking focusing on vehicular delay-tolerant networks (VDTNs).

To guarantee the success of data dissemination in vehicular networks scenarios it is important to ensure that network nodes cooperate with each other. However, it is not possible to ensure a fully cooperative scenario. This situation makes vehicular networks suitable to the presence of selfish and misbehavior nodes, which may result in a significant decrease of the overall network performance. Thus, cooperative nodes may suffer from the overwhelming load of services from other nodes, which comprises their performance.

Trying to solve some of these problems, this thesis presents several proposals and studies on the impact of cooperation, monitoring, and management strategies on the network performance of the VDTN architecture. The main goal of these proposals is to enhance the network performance. In particular, cooperation and management approaches are exploited to improve and optimize the use of network resources. It is demonstrated the performance gains attainable in a VDTN through both types of approaches, not only in terms of bundle delivery probability, but also in terms of wasted resources.

The results and achievements observed on this research work are intended to contribute to the advance of the state-of-the-art on methods and strategies for overcome the challenges that arise from the unique characteristics and conceptual design of vehicular networks.

Keywords

Mobile Ad hoc Network (MANET), Vehicular Ad Hoc Network (VANET), Delay-Tolerant Network (DTN), Vehicular Delay-Tolerant Network (VDTN), Cooperation, Vehicular Networks, Vehicular Communications, Opportunistic Networks, Reputation System, Selfish Nodes, Performance Evaluation, Reputation Mechanisms, Hybrid Approach, Cooperative Watchdog, Network monitoring, Network management, Resource management, Simulation, Urban and Rural Connectivity.

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Acronyms

AP	Access Points
ARIMA	AutoRegresslve MA
ARQ	Automatic Repeat reQuest
BAD	Bundle Aggregation and De-aggregation
BSC	Bundle Signaling Control
BT	Buffer Threshold level
C-ARQ	Cooperative ARQ scheme
CA	Cellulat Automata
CAN	Control Area Network
COIN	Open Inter-Vehicle Communication Networks
COMAD	COngestion MAnagement and Deadlock avoidance
CONFIDANT	Cooperation Of Nodes: Fairness In Dynamic Ad-hoc NeTworks
CORE	Collaborative Reputation Mechanism
CSM	Compressive Sensing based Monitoring
CWS	Cooperative Watchdog System
DC-ARQ	Delayed Cooperative ARQ
DDT	Dynamic Trust-Token
DISD	Double Increment Simple Decrement
DTN	Delay/Disruption-tolerant Network
ES	Exponential Smoothing
FLRM	Fuzzy Logic based Resource Management
FRAME	Fair Reimbursement And Motivating swEepstake scheme
FRBS	Fuzzy Rule-Based System
GPS	Global Positioning System
GSM	Global System for Mobile
GyTAR	Greedy Traffic Aware Routing
HA	Home Agent
HMIPv6	Hierarchical Mobile IPv6
ID	Identificator
INPC	Inverse Node Performance Cooperation
IP	Internet Protocol

IPv4	Internet Protocol version 4
IPv6	Internet Protocol version 6
ITS	Intelligent Transportation Systems
LA	Learning Automata
LAFTRA	Learning Automata based Fault-Tolerant Routing Algorithm
LT	Link Threshold level
MA	Moving Average
MANET	Mobile Ad-Hoc Network
MB	MegaBytes
MIPv6	Mobile Internet Protocol version 6
MIRON	Mobile IPv6 Route Optimisation for NEMO
MOCA	Mechanism for cOnnectivity management on Cognitive vehiculAr networks
MoM	MOonitoring and Management Tool
MSC	Media Service Counter
NBS	Network Mobility Support
NEMO	Network Mobility
NERON	NEst Route Optimization for NEMO
NMS	Network Management System
NN	Neural Network
NPC	Node Performance Cooperation
OBS	Optical Burst Switching
OCEAN	Observation-based Cooperation Enforcement in Ad hoc Networks
ONEMO	Optimized NEMO
OSI	Open Systems Interconnection
PCD	Popular Content Distribution
PRTMS	Predictive Road Traffic Management System
QoS	Quality of Service
REMA	REsource MAnagement
RHP	Receding-Horizon Parameterized
RLSMP	Region-based Location-Service Management Protocol
RMC	Random Mandatory Cooperation
RMS	Reputation Management System
RSU	Roadside Units

Acronyms

SCM	Services and Communications Management
SCR	Social Contribution-based Routing protocol
SFMMA	Seamless Flow Mobility Management Architecture
SIDD	Simple Increment Double Decrement
SIMHD	Simple Increment Message Hop Decrement
SINEMO	Seamless IP diversity based NEtwork MObility
SISD	Simple Increment Simple Decrement
SLNC	Symbol Level Network Coding
SMART	Secure Multilayer credit-based incentive
SMC	Static Mandatory Cooperation
SNMP	Simple Network Management Protocol
SRP	Source Routing Protocol
TCP	Transport Control Protocol
TCP/IP	Transport Control Protocol/Internet Protocol
TFT	Tit-For-Tat
TSC	Time Spent to Cooperate
TTL	Time-To-Live
UDP	User Datagram Protocol
V2I	Vehicle-To- Infrastructure
V2V	Vehicle-To-Vehicle
VAM	VANET- based Autonomous Management
VANET	Vehicular Ad Hoc Network
VARON	Vehicular Ad Hoc Route Optimization
VARS	Vehicle Ad-Hoc Network Reputation System
VBT	Volume of Bytes Transferred
VDTN	Vehicular Delay-Tolerant Network
VDTNSim	Vehicular Delay-Tolerant Network Simulator
VIME	VANET Incentive Model with Exclusion

Chapter 1

Introduction

This thesis addresses the subject of cooperation, monitoring, and management in vehicular networks, proposing cooperative, monitoring, and management methods based on the single characteristics of opportunistic vehicular environments. The focus and scope of this research programme are further described in this chapter, together with the problem definition and objectives, the thesis statement, the main contributions, and the document organization.

1.1 Thesis Focus and Scope

A vehicular network can be defined as self-organized network, where vehicles move along roads communicating with each other or with some kind of roadside infrastructure equipment, allowing messages/data to travel between their source and destination nodes. To communicate with others, vehicles are equipped with short-range wireless devices. Due to vehicles mobility, the network topology is constantly changing, resulting in a network where nodes can be located in line of sight or out of radio range if a multi-hop network is considered [1-3].

In the last few years, this kind of network began attracting the attention, not only from the scientific community, but also from governments and the automotive industry. Several automotive companies and consortiums already have in the market or are developing vehicles prototypes equipped with sensors, on-board computers and wireless communication devices [4-6]. Based on this tendency, it is expected that vehicular networks will be very likely to be deployed in the upcoming years as some real experiences already can be observed currently.

One of the main reasons for the exponential growing interest on vehicular networks is the wide range of environments and applications they support, their growing interest, and their importance on the subject. Some of these applications can have direct impact on people's daily life [7]. For example, they can be used to deploy applications aiming to improve road safety, to optimize traffic and road capacity, to inform drivers about parking space availability, or even to collect sensor data in monitoring networks. They can also be used to allow users to benefit from the use of commercial (e.g., advertisements) and entertainment applications (e.g., multimedia content sharing). Vehicular networks are not limited to be deployed in urban or developed environments. They are also capable to perform in rural/remote regions or in catastrophic environments providing connectivity or assisting communications where a conventional communication infrastructure is missing.

Despite the huge number of application scenarios, vehicular networks need to overcome several technological challenges. Some of these issues are shared by wireless and ad hoc networks while others arise from the particular properties of vehicular networks. The highly dynamic network topology is one of these problems, if not the major one. It is directly related to vehicles speed and mobility, which leads to short and sporadic contact opportunities [1-3, 8].

To increase the impact of the above-presented issue, vehicular networks suffer from limited transmission ranges, radio obstructions inflicted by physical factors (e.g., building walls and obstacles), and interferences (e.g., congested channels caused by overpopulated environments). Combining all these factors it is easy to understand why vehicular networks are suitable to disruption, intermittent connectivity, frequent fragmentation, and significant loss rates, resulting on a possible absence of an end-to-end path between source and destination nodes.

Trying to overcome some of these issues, several network architectures were proposed. Vehicular Ad Hoc Networks (VANETs) [9, 10] exploit vehicles as mobile nodes, exposing them to traffic conditions and regulations. In this kind of architecture, vehicles may interact among them or with roadside infrastructures. Following this approach, most of the applications for VANETs consider three different types of methodologies to enable communications between network nodes [11-13]: Vehicle-to-Vehicle (V2V) ad hoc network, a wired backbone with wireless last hop (Vehicle-to-Infrastructure - V2I), and a hybrid approach combining both. Common to all communication methodologies is the assumption of an end-to-end connectivity. This makes VANETs suitable to network partition, long time delays, and disconnection.

The Delay-Tolerant Network (DTN) architecture [14-17] tries to improve the network reliability by supporting intermittent communications between network nodes. This architecture overlays the bundle layer under the application layer, which allows the deployment of a store-carry-and-forward paradigm. This paradigm exploits the high mobility of mobile nodes to enable network communications building a hop-by-hop session for data transfer.

Following the DTN approach and gathering contributions from other technologies, Vehicular Delay-Tolerant Networks (VDTNs) [18, 19] propose an out-of-band signaling with control and data planes separation. Contrary to DTNs, VDTNs places the bundle layer under the network layer, allowing to forward larger packets (called bundles) aggregating IP (Internet Protocol) datagrams. The control plane is used to exchange signaling messages aiming to reserve resources that will be used by data plane and to help in the scheduling decision process. On the other hand, the data plane is mainly used for data transport and exchange, buffer management, and traffic classification. This architecture considers three different kinds of nodes: terminal, relay, and mobile nodes. Terminal nodes are responsible to generate and receive data. Relay nodes are usually placed at crossroads and have a large store capability, which allows them to store a huge amount of data that will be forwarded to mobile nodes when a contact opportunity is available. These devices also aim to increase the number of contact opportunities, which will result in a higher probability of data being delivery [20]. Finally, mobile nodes move along roads collecting and delivering data to its final destination. Mobile nodes can also act as terminal nodes when generate and/or are the final destinations of a communication.

Although the advances achieved in the last years by the studies conducted in the above-presented architectures, vehicular networks still face several research challenges that must be overcome. These challenges include resource management (e.g., power, buffer) and cooperative communications among network nodes (e.g., routing, data dissemination). Both fields of research are very important and challenging due to their complexity. For this reason, the research performed in the scope of this research programme, focuses on the inherent problems in cooperative communications, monitoring, and management functionalities in opportunistic vehicular networks. These problems will be studied through the proposal and performance

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assessment of cooperative and monitoring/management methodologies considering the VDTN architecture.

1.2 Problem Definition and Research Objectives

This thesis addresses the problematic of cooperation among network nodes and how the VDTN architecture may perform monitoring and management functionalities aiming to improve its overall network performance and the confidence in the use of vehicular networks. The importance of these two research fields stems from the requirement that the increasing complexity of vehicular networks brought, requiring the creation of more sophisticated tools and strategies. In VDTNs, cooperation tries to overcome the possible nonexistence of an end-to-end path between data origin and destination, through a resource sharing approach between network nodes. In turn, management and network monitoring seeks to maintain a clear view of the state of the network, addressing and correcting problems as they arise.

Regarding cooperation, most of the published studies concluded that, in vehicular networks, nodes must cooperate in order to improve the overall network performance. However, enforcing cooperation in vehicular communications is not an easy task and raises several technical challenges. It is very important to study the best way to stimulate nodes to cooperate avoiding them to diverge from the protocol. Nodes with such behavior have a negative impact in the network and severely comprises its overall performance. For example, a node may tend to have a selfish behavior and be unwilling to forward messages from others because it does not win anything with it. Furthermore, carrying messages from others force nodes to share their own storage space. Another example of a node that tends to diverge from the protocol is a node with an active mobility on the road (e.g., taxis, cars, buses, and trucks). This type of nodes has a huge probability to be picked as forwarders. However, and despite others nodes that are always willing to cooperate, they have to face the overwhelming load of services from other nodes. This situation will consume nodes resources soon, such as wireless bandwidth or storage capacity that will force them to diverge from the protocol in order to avoid compromising/deteriorating its own data or resources. Several approaches may be adopted to avoid nodes to diverge from the protocol. Cooperation mechanisms may be proposed to assist routing protocols and data dissemination strategies to select the best path between source and a destination points, forwarding bundles only to the best forwarders nodes. Another possible solution is to stimulate them to cooperate giving incentives to them. This may be achieved by proposing cooperative strategies that reward/punish nodes according to their cooperative behavior.

Enforcing cooperation between nodes improves significantly the network operation, however is not enough to achieve an optimal performance. Usually, this kind of networks has several resource constraints (e.g., energy, storage). It is essential to have network strategies that perform monitoring and management functionalities to prevent, detect, and solve network anomalies or constraints, allowing the optimization of nodes resources utilization. For example, if a node moves along roads with low power capabilities or storage constraints, it is important to detect it, and notify all other nodes to avoid communications with it. Forwarding bundles to constrained nodes severely comprises their changes to reach the final destination, since this kind of nodes may run out of power excluding themselves from the network, or may have to adopt a dropping policy to have enough space to continue consuming network resources. A pos-

sible solution to minimize the impact of resources limitations is to create tools for monitoring purposes capable to collect real-time information about nodes and network performance state that can be used by network administrators to detect network constraints and enforce measurements to solve them, contributing to improve the overall network performance.

Quality of service may also be guaranteed by management approaches. The dynamic mobility and ad hoc nature of vehicular environments does not allow the adoption of resource reservation techniques used in traditional networked environments. In vehicular communications, this functionality is usually ensured by routing protocols that are designed to be responsible for the entire network self-managing. However, external solutions that perform management and monitoring functionalities may be desirable to optimize parameters of routing protocols. Such approach may lead to more stable topologies and lower control traffic overhead increasing the delivery ratio and decreasing the end-to-end delay and the consumption of bandwidth and energy.

The above-presented observations motivate the proposal of new cooperation and network management/monitoring solutions for vehicular networks. Therefore, the main objective of this research programme is to present a proposal of cooperative and monitoring/management approaches for VDTNs. Moreover, performance evaluation studies of these proposals are needed in order to analyze their applicability. To accomplish this main objective, the following intermediate objectives were identified:

- Comprehensive and meaningful review of the state of the art on opportunistic networks, their most relevant services and applications, and available strategies to deal with cooperation, management, and monitoring functionalities on vehicular and delay-tolerant networks. This will allow identifying and understanding, in detail, vehicular and delay-tolerant networks characteristics, limitations, and challenges. Moreover, it will allow identifying several open issues and gathered contributions from the existing approaches.
- Proposal, creation, and validation of cooperative strategies for VDTNs. These strategies should use the out-of-band signaling to introduce cooperation into control and data plane. This will allow nodes to contribute to the increase of the overall network performance, not only by sending bundles but also by sharing their storage capacity to store bundles from others. Performance assessment analysis will be performed to evaluate the impact of cooperation in the VDTN performance.
- Proposal and creation of sophisticated systems to deal with the presence of selfish and misbehavior nodes in the network. Based on the problems and open issues identified on previous studies, these systems will focus on improving the overall network performance by considering different mechanisms to reward/punish nodes by their cooperative/uncooperative behavior in order to promptly detect and avoid/exclude selfish nodes from the network. To classify nodes according to their cooperative behavior, proposed systems will consider different reputation mechanisms. Some may rely their operation in a cooperative exchange of nodes reputation score across the network, while others may calculate nodes reputation score according to their performance on the network. Performance studies will be conducted to deploy all systems in the VDTN network considering

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two different kinds of scenarios: urban and rural. This will allow the evaluation of their impact in the VDTN performance under different network conditions.

- Proposal and performance evaluation of hybrid strategies that combines reputation-based approaches with incentive mechanisms to instigate selfish or misbehavior nodes to cooperate. Contrary to the previous systems, hybrid approaches are intended to encourage selfish nodes to share their resources with others, instead of immediately avoiding or excluding them from the network. To accomplish such goal incentive mechanisms will be created. Performance studies will be conducted to compare the impact of both incentive and reputation approaches in the performance of VDTNs.
- Proposal, design, and performance evaluation of monitoring tools to detect and deal with constrained nodes. To operate these tools, it is needed to collect real-time information regarding nodes performance and network state. Moreover, monitoring tools must be capable to react to constraints detection, performing some kind of actions to minimize their impact on the network. Performance studies will be conducted aiming to assess the impact of monitoring approaches on VDTNs.
- Proposal, construction, and validation of resource management strategies, which aim to support routing protocols to minimize the network resources consumption. These strategies will be afforded with sophisticated scheduler systems that take into consideration resources limitation and the best interests of the network to forward bundles. Performance studies will be conducted to evaluate and demonstrate all strategies applicability and reliability.

1.3 Research hypothesis

This thesis proposes several approaches and strategies focused on cooperation, monitoring and network management aiming to improve the performance of VDTNs. Specifically, the thesis statement is:

The performance of VDTNs relies on nodes cooperation and how they consume network resources. The cooperation level of each network node may be measured through the percentage of resources shared with others. The resources shared with other nodes may include sharing a percentage of the storage capacity to store bundles generated by others, or spending some time at each contact opportunity sending bundles from others aiming to deliver them to their final destination. Hence, avoiding communications with selfish or misbehavior nodes contributes to increase the network efficiency by increasing the bundle delivery probability and decreasing the amount of resources waste. Network resources consumption may also be attenuated through the constant network monitoring in conjunction with sophisticated mechanisms that schedule bundles considering the increasing of the network performance.

To support this thesis statement, the following research approach was adopted:

The progress and evolution of vehicular technologies, services, and applications was carefully studied. Through this study the most common architectures for vehicular networks were identified, as well as their limitations and challenges. Moreover, two detailed studies on cooperative approaches and monitoring/management strategies applied to vehicular networks were performed. Through these studies, several contributions were presented and used as a starting point for the proposal of novel applications for both fields.

Regarding cooperation, and based on the challenges and limitations identified by the previous study in the cooperation field and with the gathered contributions from the already existing approaches, several strategies were proposed. Two different levels of cooperation were considered and studied. At the first level, cooperation is enforced at nodes buffer where nodes are forced to share a percentage of their buffer capacity to store bundles from other nodes. The second level of cooperation considers cooperation at the data plane. In this case, nodes are enforced to share a percentage of time at each contact opportunity to send bundles from other nodes.

Then, to better understand the impact of cooperation in VDTNs, four cooperation strategies were proposed to force nodes to share a certain percentage of their own resources with others. The percentage that nodes share with others is estimated considering different approaches: *i)* fixed and pre-defined value set at the beginning of the network operation; *ii)* random value calculated each time a contact opportunity is available; *iii)* according to nodes performance. To demonstrate the advantages of these proposals, a performance evaluation analysis was conducted through a build-up simulation scenario that was deployed in the VDTNsim tool [21].

The presence of selfish and misbehavior nodes, which severely comprises the network and cooperative nodes performance was also considered. To minimize the impact of such nodes in VDTNs, three solutions were proposed: a reputation, a hybrid, and a watchdog. All the proposals manage to detect selfish or misbehavior nodes, and while some immediately exclude them from the network, others try to stimulate them to cooperate. The reputation system was proposed considering nodes reputation scores calculated through nodes performance. For example, each time nodes successfully deliver a bundle, their reputation increases. However, each time they drop a bundle without send it, at least, once, their reputation decreases. This system also considers four different ways to penalize nodes with a selfish behavior. All of them distinguish itself from others by the way they reward/penalize nodes by their behavior. Each time a node has a reputation below the cooperative threshold it is immediately marked as selfish node and is excluded from the network. The reputation system performance and applicability was assessed through performance studies conducted over simulation in two different kinds of scenarios: urban and rural. Thus, with the information gathered from the previous proposal, a hybrid system was developed aiming to incentive selfish to cooperate by sharing their resources. This system takes advantages from the reputation system to calculate nodes reputation score. Then, when a selfish node is detected, instead of being immediately excluded from the network it is encouraged to cooperate. To achieve such goal two incentives strategies were proposed. Performance assessment of this system show that this approach manages to increase the VDTN performance when compared to the reputation system approach. The last proposal to deal with misbehavior nodes in VDTNs was a cooperative watchdog system. Its operation relies on a cooperative exchange of nodes reputation along the network. Each time a contact opportunity is available, it updates nodes reputation score according to the considerations of three distinct modules:

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classification, neighbor's evaluation, and decision. When a selfish node is detected, an alarm is spread by the entire network. Performance studies showed that the cooperative watchdog proposed for VDTNs is not only effective in detecting misbehaving nodes but also contributes to improve the overall network performance by increasing the bundle delivery probability and decreasing the amount of resources waste.

The observations made in the cooperation field showed a significant improvement of the network performance. However, the same remarks also enabled the identification of a resource consumption problem regarding high cooperative nodes. This problem is related to their storage and power capacity. High cooperative nodes tend to quickly reach its full storage capacity. This happens due to the high number of contact opportunities they participate, receiving bundles from others in order to deliver them to a next waypoint or to their final destination. In order to overcome this condition, and based on the state of the art, network monitoring and management methodologies were proposed aiming to assist routing protocols and administration tools to enhance VDTNs overall performance. In this sense, two management and monitoring approaches were proposed. The first is a monitoring tool capable to detect constraint nodes by collecting real-time information regarding nodes and network state. Conducted studies shown a significant improvement on VDTNs not only in terms of bundle delivery probability but also in the amount of wasted resources. Finally, a resource management tool, called REMA, was proposed with objective to help routing protocols to minimize the consumption of networks resources. This is achieved by deploying a sophisticated scheduler that forwards bundles considering the best interests of a VDTN network. Performance evaluation studies conducted through simulation shown that REMA significantly decreases the amount of wasted resources, increases the bundle delivery ratio, and decreases the overhead ratio.

1.4 Main Contributions

This section is dedicated to the main scientific contributions of this thesis. Thus, the following paragraphs describe the main proposals for the advance of the state of the art in the field of VDTNs.

The first contribution of this thesis is a detailed and comprehensive analysis of the state of the art related with cooperation strategies for vehicular communications and delay-tolerant networking, which is presented in Chapter 2. A survey providing a deep review and discussion of current representative approaches to implement cooperation in vehicular environments, has been published in the inaugural issue of the *Elsevier Vehicular Communications Journal* [22]. In 2016, this article received a mention as one of the most cited articles since 2011.

The second contribution is the proposal and performance evaluation of two cooperation levels based on the out-of-band-signaling approach of VDTNs, which is presented in Chapter 3. This proposal was published in the *Mobile Networks and Applications (MONET)* journal, from Springer, at the special issue on *Network Protocols and Algorithms for Vehicular Ad Hoc Networks* [23].

The third contribution, presented on Chapter 4, is the proposal and the deployment of four different cooperative schemes to enforce cooperation in VDTN nodes. This proposal de-

scription and validation was published in the *European Transactions on Telecommunications* journal, from Jonh Wiley and Sons [24].

The fourth contribution is the proposal and construction of a reputation system to detect, identify, and avoid communications with selfish nodes, presented in Chapter 5. A preliminary version of this proposal was presented at the *13th International Conference on ITS Telecommunications (ITST 2013)* [25], in Appendix A. An improved version and the detailed study of this proposal was published by the *EURASIP Journal on Wireless Communications and Networking*, Springer [26].

The fifth contribution is the proposal of two strategies to encourage selfish nodes to adopt a cooperative behavior, which is described in Appendix B. To evaluate the impact of the proposed incentive strategies, a hybrid system was implemented taking advantages of the already proposed reputation system to identify selfish nodes. This contribution was presented at the *2015 IEEE International Conference on Communications (IEEE ICC 2015)* [27].

The sixth contribution is the proposal and the implementation of a cooperative watchdog system to detect, classify, and act against selfish nodes aiming to improve the performance of VDTN networks, which is presented in Chapter 6. The proposal and performance assessment study of this contribution has been published in a joint *Special Section on Connected Vehicles - Advancements in Vehicular Technologies and Informatics by the IEEE Transactions on Industrial Electronics and IEEE Transactions on Industrial Informatics* journals [28].

The seventh contribution, included in Chapter 7, analyses the influence of cooperative strategies to increase the VDTN network performance, considering scenarios where some nodes may not be able to cooperate. This work also intended to do a brief tutorial about how to design cooperative strategies for VDTNs. It gives an overview of the field, providing several motivations and major challenges. It has been published in the *IEEE Communications Magazine* [29].

The eighth contribution is a detailed review of the state of the art on management and monitoring approaches for vehicular and delay-tolerant networks, which is presented in Chapter 8. A survey providing a detailed review of the related literature, discussion and identification of open issues on this topic has been submitted to an international journal.

The ninth contribution is presented and analyzed in Appendix C. It considers the proposal and performance analysis of a monitoring tool for VDTNs capable to collect real-time information in order to detect networks constraints. This contribution was presented at the *8th International Conference on Ubiquitous and Future Networks (ICUFN 2016)* [30].

The tenth contribution is the proposal and evaluation of a resources management mechanism to deal with nodes storage and energy constraints. This contribution is included in Chapter 9 and has been published in *Elsevier Vehicular Communications Journal* [31].

The last contribution of this thesis is the proposal of two new modules (cooperation and network monitoring/management) for the VDTNSim simulator [32] (available for download at <http://vdtm-sim.it.ubi.pt>). Both modules allow evaluating the performance of methodologies and mechanisms to deal with misbehavior nodes, either by a selfish behavior or by some kind of

constraint.

1.5 Thesis Organization

This thesis consists on ten Chapters, which are organized as follows. The first chapter presents the scope of the thesis, focusing the topics under study, the definition of the problem and main objectives. The research hypothesis, the main contributions, and the document's organization are also included in this chapter. Except this and the conclusions chapter, all the others are based on an article published in or submitted to an international journal. In Appendix, three contributions presented in international conferences are described and analyzed.

Chapter 2 presents a survey focusing on cooperation in vehicular and delay-tolerant networks, entitled "*Cooperation advances on vehicular communications: A survey*". It also identifies several open issues that may be used as a starting point to propose new and better approaches to deal with cooperation in VDTNs.

Chapter 3, entitled "*The Impact of Cooperative Nodes on the Performance of Vehicular Delay-Tolerant Networks*", studies and proposes two levels of cooperation for VDTNs, considering buffer space and connection-time sharing. It also demonstrates the role of cooperation as one of the key factors to improve and optimize the overall network performance. In Chapter 4 ("*Performance evaluation of cooperative strategies for Vehicular Delay-Tolerant Networks*"), four different schemes to impose cooperation in VDTNs are proposed and their performance are analyzed by applying them on the most popular routing protocols for DTN-based networks (Epidemic [33] and Spray and Wait [34]).

Chapter 5 presents a study addressing the applicability of a reputation system in VDTNs to deal with the problem of selfish and misbehavior nodes, entitled "*Performance evaluation of a cooperative reputation system for vehicular delay-tolerant networks*". In this context, several other studies are conducted to minimize the impact of selfish nodes in the network. Chapter 6 ("*A Cooperative Watchdog System to Detect Misbehavior Nodes in Vehicular Delay-Tolerant Networks*") describes a cooperative watchdog for the VDTN architecture, which was designed and developed to detect, identify, and act against misbehavior nodes.

Chapter 7, entitled "*Cooperation strategies for vehicular delay-tolerant networks*", summarizes all the proposed approaches to deal with cooperation in VDTNs presenting a performance evaluation study comparing the best performing approaches.

Chapter 8 presents a detailed survey regarding network management and monitoring strategies for vehicular communications, entitled "*Network Management and Monitoring Solutions for Vehicular Communications*". It also presents several open issues that may be considered as a starting point to propose new and better approaches to deal with network monitoring and management in VDTNs.

Chapter 9 ("*REMA: A Resource Management Tool to Improve the Performance of Vehicular Delay Tolerant Networks*") presents experiments on improving the performance of VDTNs through a tool that deals with storage and energy constraints.

Finally, Chapter 10 concludes the thesis, summarizing the main research findings and suggesting future research directions.

In Appendix, several contributions presented in international conferences are presented and described. In Appendix A, a preliminary study of the reputation system described in Chapter 5 entitled “*A Reputation System to Identify and Isolate Selfish Nodes in Vehicular Delay-Tolerant Networks*” is presented and described.

In Appendix B, an experiment on improving the performance of VDTNs networks, entitled “*A hybrid system to stimulate selfish nodes to cooperate in Vehicular Delay-Tolerant Networks*”, is presented. This experiment considers a hybrid approach to encourage selfish nodes to share their resources.

Appendix C presents a study about the applicability of a monitoring tool to provide monitoring capabilities to the VDTN network, entitled “*MoM - A Real Time Monitoring and Management Tool to Improve the Performance of Vehicular Delay Tolerant Networks*”.

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Chapter 2

Cooperation advances on vehicular communications: A survey

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Review

Cooperation advances on vehicular communications: A survey

João A.F.F. Dias^a, Joel J.P.C. Rodrigues^a, Liang Zhou^b^a Instituto de Telecomunicações, University of Beira Interior, Covilhã, Portugal^b Nanjing University of Posts and Telecommunications, China

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ABSTRACT

Vehicular communications refer to a wide range of networks adopted in environments characterized by sparse connectivity, frequent network partitioning, intermittent connectivity, long propagation delays, asymmetric data rates, and high error rates. These environments may also be characterized by a potential non-existence of an end-to-end path. Cooperation among network nodes is crucial to address these challenging connectivity issues. In order to contribute for a better network performance, network nodes should to share their storage, bandwidth, and energy resources with each other. By sharing their resources each node contributes to store, carry, and forward network data in order to mutually enhance the overall network performance. However, not all network nodes are able to cooperate and sometimes they may have an uncooperative behavior in order to save their own resources. Such behavior severely affects the network functionality and performance. Then, this survey overviews the most recent advances related to cooperation on vehicular communications. The goal of this work is not only to present how cooperation between network nodes has advanced, but also to show the benefits and drawbacks of cooperation, and to identify open issues providing guidelines for further contributions in this type of networks.

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1. Introduction

In the last decades, wireless networks have been considered to enable communications between any kinds of mobile devices (e.g., personal computers, smartphones, sensors) [1]. Due to their massive acceptance by the research community different wireless networks standards have emerged allowing easy deployment of applications. However, the deployment of such networks where a network infrastructure is not available may be a challenging task. To solve some of the issues related to wireless networks deployment, Mobile Ad-Hoc Networks (MANETs) [2,3] were proposed. In such networks, a collection of mobile nodes (i.e., mobile devices) equipped with wireless devices directly communicate with each other, creating a temporary self-organized network with a random topology without a centralized infrastructure [4]. This is particularly useful because it allows the deployment of such networks in a wide range of scenarios (e.g., coordination of rescue efforts in emergency situations and operation in remote areas) [5].

Recently, and taking advantages of the research work progresses achieved in MANETs, the automotive industry and the research community joint efforts to propose new architectures based in vehicular communications. In vehicular networks, vehicles are exploited in order to deploy a considerable number of applications

and services. By definition a vehicular network is a spontaneous and self-organized network, where vehicles equipped with short-range wireless devices, communicate with each other to allow communications with roadside infrastructure equipment or with other vehicles [6–8]. In such networks, nodes may be located in line of sight or out of the ratio range depending on the amount of nodes that contribute to a multi-hop network.

Vehicular networks have a wide range of applications that may influence our daily life [7,9]. For example, they may be used to improve road safety, to optimize traffic flow or road capacity. They can also be used for monitoring purposes, such as monitoring networks for sensor data collection. Vehicular networks may also be applied to deploy commercial and entertainment applications (e.g., commercial advertisements, parking space availability, and multimedia content sharing). Lately, this type of networks has been used to provide connectivity to rural communities or remote regions, and to support communication between rescue teams and other emergency services in catastrophe scenarios.

Despite of their applicability, vehicular networks faces a number of technical challenges that must be overcome to make these networks widely considered. The highly dynamic network topology is one of these challenges and arises from the high mobility and speed of vehicles. This also led to short contact durations. Vehicular networks are also characterized by intermittent connectivity and significant loss rates. Such characteristics are a consequence of limited transmission ranges, radio obstacles (e.g., terrain, vegetation, buildings and tunnels) and interferences (e.g., high congestion

E-mail addresses: joao.dias@it.ubi.pt (J.A.F.F. Dias), joeljr@ieee.org (J.J.P.C. Rodrigues), liang.zhou@ieee.org (L. Zhou).

channels caused by high density of nodes). Vehicular networks are also characterized by the lack of an end-to-end path between the source and destination nodes, which results in a small effective network diameter.

To overcome the above-presented issues several architectures have been proposed, such as Vehicular Ad-Hoc Networks (VANETs) [6–11], Delay/Disruption-Tolerant Networks (DTNs) [12], and Vehicular Delay-Tolerant Networks [13]. In VANETs, vehicles are exploited as mobile nodes to allow communications between all network nodes. These communications may be categorized into Vehicle-to-Vehicle (V2V) or Vehicle-to-Infrastructure (V2I). In both approaches an end-to-end path is assumed. Nevertheless, VANETs are not able to deal with network partition, disconnection and long time delays.

DTNs proposed the store-carry-and-forward paradigm in order to deal with several open issues presented by VANETs. In DTNs vehicles are used to transport data between disconnected parts of the network. If a contact opportunity is not available, data is stored until a new contact opportunity. When this happens, data is forwarded based on a specific routing protocol, in order to reach its final destination. VDTNs appear as a novel approach for vehicular communications and gather several contributions from the above-presented architectures. In VDTNs, three node types are considered: terminal, relay and mobile. Terminal nodes may be fixed or mobile devices that are responsible for the origin or destination of data. Relay nodes are stationary devices that are placed at roadside intersections. These devices have storage capabilities in order to store and forward large amount of data. By placing these devices in crossroads, the number of contact opportunities increases and consequently increases the probability of data being delivery [14].

Despite all the above-mentioned architectures solve some of the stated issues found in vehicular networks, there are still open issues that should be solved. One of them is cooperation between networks nodes. Even whether a routing protocol has a good performance when deployed into a vehicular network, it is still important to ensure that all the network nodes follow the pre-defined protocol. This problem should be carefully studied if two types of nodes are considered. The first type is an ordinary node that belongs to an individual user. This node is characterized for being selfish and unwilling to forward messages to others in exchange of nothing. Furthermore, carrying messages from other users force nodes to share their own storage space. The other type of nodes is a node with active mobility on the road (e.g., taxis, cars, buses, and trucks). This type of nodes has a huge probability to be picked as forwarders. However, and despite of these nodes are willing to cooperate, they have to face the overwhelming load of services for other nodes. This will consume resources soon, such as wireless bandwidth or storage space that will force nodes to diverge from the protocol in order to avoid compromising its own data or resources. In order to avoid nodes to diverge from the protocol, they should be stimulated to cooperate. To do that it is highly important to give them incentives.

Several contributions were performed in wireless networks that may be considered for vehicular networks. In wireless networks there are two types of incentives: reputation-based approaches [15–17] and credit-based approaches [18,19]. In the reputation approach nodes observe their neighbors, punishing them if they are not cooperating. On the other hand, in the credit-based approach nodes collect credits as a reward by their cooperative behavior. These approaches cannot be directly applied to vehicular networks since an end-to-end path is not ensured. However, the main concepts of these approaches may be used to proposed new approaches or to adapt the already proposed approaches.

In this paper the most important cooperation proposals and approaches for vehicular networks are discussed and analyzed. This study is intended to be a helpful tool for the creation of new co-

operation approaches to be deployed on VDTNs. Then, this paper aims to show how cooperation mechanisms are adapted to vehicular networks in order to improve the overall network performance (i.e., increase the message delivery ratio and decrease the waste of resource consumption) by presenting and classifying the most recent and relevant proposals of cooperation approaches for vehicular networks. Moreover, a discussion and open issues on cooperation techniques for vehicular delay-tolerant networks are identified to facilitate further contributions. Thus, the main contributions of this paper are the following:

- A review of the state of the art considering the most relevant contributions on cooperation approaches for different kinds of vehicular networks, considering VANETs, DTNs, and VDTNs;
- A discussion and open issues on cooperation techniques for vehicular networks are identified in order to facilitate further contributions.

The remainder of this paper is organized as follows. Section 2 details on VANET architecture and how this architecture deals with cooperation between nodes. Section 3 summarizes the DTN architecture and enumerates the most important works on related cooperation mechanisms. Section 4 overviews the state-of-the-art on VDTNs and analyzes several strategies to deploy cooperation strategies in such architecture, while Section 5 presents a comparative analysis between all the presented cooperation approaches, discussing and identifying some open research issues. Finally, Section 6 concludes the paper and points some directions that may be considered for future work.

2. Vehicular Ad Hoc Networks

In this section the most important contributions on cooperation in Vehicular Ad-Hoc Networks (VANETs) are presented and discussed. Vehicular Ad Hoc Networks (VANETs) were proposed as a specific type of MANETs [2,3]. The main difference between them is that mobile nodes are vehicles. Such difference limits nodes to only move on roads, which are subject to traffic flow and traffic regulations. In VANETs, vehicles may communicate with other vehicles (V2V) or with roadside infrastructures (V2I). In the literature several approaches and architectures are considered to implement the communication links between vehicles [20]. Most of them considered three types of architectures: a pure V2V ad-hoc network, a wired backbone with wireless last hop, or a hybrid architecture combining the previous two.

Although the similarities with MANETs, in VANETs traditional MANET protocols cannot be directly applied. The reason for this situation is mainly due to the huge difficulties of traditional routing protocols in dealing with networks with frequent fragmentation and rapid topology changes [21,22]. Therefore, the already proposed routing protocols for MANETs must be adapted in order to deal with the unique features of VANETs.

Another solution is to design new routing protocols. To design new routing protocols for VANETs it is important to keep in mind that different VANET applications have different requirements. For example, a single routing protocol is not capable to self-adapt to different applications that use distinct transmission facilities (e.g., unicast, broadcast, or multicast). Lin et al. [23] proposed a taxonomy that divides routing protocols into three categories: unicast, multicast/geocast, and broadcast. Unicast routing establishes a source-to-destination path. Multicast routing is used to deliver data from one specific source to all the interested receptors. Geocast routing is used to deliver data to a specific geographic region. Finally, broadcast routing is used to deliver data to all nodes in the network.

In order to improve the overall network performance is not enough to design routing protocols that consider all the characteristics of VANETs. It is also extremely important to combine routing protocols with other features such as cooperation mechanisms between nodes. The next subsection overviews the most important contributions related to cooperation approaches for VANETs.

2.1. Cooperation approaches for VANETs

A well-built cooperative system can produce many benefits when compared to traditional systems [24–26] by increasing the overall network performance due to an increase of the delivery data rate with fewer transmissions. This results in the increase of the network throughput. It also allows nodes without data connections to access Internet services, creating a balanced QoS network. A fully operational cooperative system also helps to reduce costs by using relay nodes to decrease the network infrastructure dependency.

As a subset of MANETs, it was expected that cooperation mechanisms proposals for this type of networks could be directly applied into VANETs. However, they cannot be directly applied. Nevertheless, the way MANETs stimulate nodes to cooperate should be considered in order to adapt them to be deployed into VANETs [27]. In MANETs there are two types of cooperative approaches: reputation-based and pricing-based mechanisms [28]. At the reputation-based systems, nodes with a selfish behavior are isolated from others nodes and eventually they are deprived from receiving any services from them, while cooperative nodes are rewarded. This approach is highlighted in [16] where authors studied several countermeasures to address with selfish behavior of nodes. Most of them rely on neighbor monitoring in order to calculate their trustiness [29].

Following the reputation-based approach several reputation systems were proposed. For example, CONFIDANT scheme [30,31] incentive nodes to cooperate by detecting and isolating misbehavior nodes. To perform such task, this scheme implements a system in every node composed by four main components: a monitor, a trust manager, a path manager, and a reputation score. The monitor helps nodes to detect any misbehavior node, while the trust manager use the information collected by the monitor to make routing decisions. The path manager calculates the optimal path by avoiding malicious nodes. To calculate the optimal path the reputation score of each node is considered.

CORE scheme [16] uses three different reputation types to select which nodes can use network services: subjective, calculated based on direct observation; indirect reputation calculated according to information provided by other nodes; and functional reputation calculated using a specified function. OCEAN [32] scheme uses a monitoring system with a reputation score in order to calculate which nodes are performing in the network with a selfish behavior. Nodes that diverge from protocol are divided into two groups: misleading and selfish groups. Misleading nodes are nodes that are part of a route finding but don't forward any packet, while selfish nodes don't make part of a route finding and consequently don't forward any packet. If a node reputation score is lower than a pre-defined threshold, then the node is added to a black list and avoided by all other nodes.

Another approach for reputation-based mechanisms is to combine or adapt some features of the above-presented schemes. For example, in [33], the authors propose a reputation system that has as main goal to encourage cooperation between nodes and punish selfish nodes. This system is implemented under the principle that cooperation between nodes is performed forwarding packets without any loss or performance degradation. To avoid misbehavior nodes, this scheme detects and punish nodes using a Reputation Management System (RMS) as an extension of the Source Rout-

ing Protocol (SRP) [34]. Together with the RMS this scheme try to convince selfish nodes to cooperate presenting them the benefits of being cooperative hoping that they can become cooperative nodes. With this scheme it was also introduced the concept of suspicious node as a partially cooperative node.

Several routing protocols were also proposed using cooperation as a main principle. For example, in [35], the authors proposed a routing protocol called Learning Automata based Fault-Tolerant Routing Algorithm (LAFTRA) that use Learning Automata (LA) to optimize the selection of paths by avoiding faulty nodes. To classify nodes into healthy or faulty nodes, this routing protocol uses a "goodness value" that is increased each time a packet is successfully forwarded and decreased each time a packet delivery failure is detected. Nodes with higher a "goodness value" will be choose as priority nodes in order to create a path between the source and destination nodes with the highest number of healthy nodes. This approach will ensure a higher packet delivery rate than any other path. Sukumaran and Blessing [36] proposed a routing protocol that makes use of mobile agents in order to calculate the best possible route between two network nodes. To calculate the best route, the proposed routing protocol uses a selfish node isolation method that calculates a node reputation score based on its behavior. A node reputation score is calculated as the ratio between the forwarded packets by this node and the total number of forwarded packets. When a node reputation score is lower than a specified threshold, the node is isolated and banned from network services. Following the same approach of this scheme, other proposals can be found in the literature as may be seen in [37–39].

Pricing-based incentives present themselves as an alternative to the above-presented reputation-based approaches. Chen and Kishore [40] proposed a cooperation strategy using a two-user approach and a pricing policy to encourage users to cooperate and guarantee benefits from that, which leads to a decrease of the message delivery delay. With this approach each time a node cooperates it is rewarded being paid by the user who asks for cooperation. Mathews et al. [41] presented a dynamic pricing approach that uses a routing scheme that gives two choices to network nodes. This is, nodes can decide which route to follow, if a route with least virtual cost or a route with QoS that results in a higher cost for them. As expected, in this model with the increase of the number of possible routes, the price to pay to use one of them decreases. Consequently, a cooperative node will have more options in what concerns to route selection. Similar schemes can be found in the literature [42,43] that uses as base the above-presented schemes in order to propose economical mechanisms that dynamically manage the cost and routes improving the overall network performance and decreasing the energy consumption.

Following the MANETs approach, several cooperation mechanisms for VANETs have already began to be published. For example, Chen et al. [44] proposes a scheme to stimulate cooperation between network nodes based on a coalitional game theory. With this scheme nodes are rewarded every time they cooperate with another one. By rewarding nodes, this scheme rigorously shows that nodes faithfully following the established routing protocol. To ensure that the best interests of each node is preserved this scheme considers the nodes storage space limitations.

In [45], the authors propose a reputation system for VANETs called Vehicle Ad-Hoc Network Reputation System (VARS). This reputation system uses two main concepts: the generation of opinions and the confidence decision. When a message arrives, the receptor generates an opinion on the trustworthiness of this message. An opinion is calculated from indirect trust (if the sender is known), from the partial opinions attached to the message, or from a combination of both. This generated opinion is attached as another partial opinion to the message before it is forwarded. The confidence decision is calculated by verifying the constraints based

on reputation levels. When a message is marked as a trusty message, this will be announced to all the network nodes.

P. Caballero-Gil et al. [46] propose a scheme to stimulate cooperation between nodes in VANETs. This scheme implements a constant share reward, which is promised by the source node to each intermediate node. When the packet reaches its final destination, each node that participated in the forwarding process should report its contribution to the source node. Afterwards, the final contribution is calculated through the sum of the partial contributions given by each node in the forwarding tree. Each intermediate node will receive a percentage as a reward for forwarding the message.

In [47], the authors propose a dynamic trust-token (DDT) based on cooperation enhancement mechanism. The main goal of this proposal is to detect and prevent nodes with uncooperative behavior to interfere with the packet transmission. This will guarantee the packet integrity during all the delivery process. With the proposed mechanism, data packets are forwarded hop-by-hop containing a token in order to evaluate its correctness. Packet-acceptance decisions will be made according to the token-proved evaluation correspondingly. The reputation of each node is set up based on runtime performance.

Jerbi et al. [48] proposes the improved Greedy Traffic Aware Routing protocol (GyTAR). This routing protocol makes use of unique characteristics of cooperative environments (e.g., road traffic density, highly dynamic vehicular traffic, and road topology) to make the routing and forwarding decisions. The selection of the next hop is made based on the scores attributed to each intersection. These scores are determined based on dynamic traffic density information and the curve metric distance to destination. In [49], the authors presented CodeOn which is a high-rate cooperative Popular Content Distribution (PCD) for VANETs. In this scheme a Symbol Level Network Coding (SLNC) [50] technique is used in order to change the traditional packet level network coding. With this technique instead of using packets to calculate the error rate it is used only a symbol, which enhances the reception reliability and thus the downloading rate. The propagation of popular contents through the network is performed by specific cooperative relay nodes dynamically selected for this purpose.

In [51], the authors use cooperation between vehicles to create a distributed media service scheme in Peer-To-Peer (P2P) based vehicular networks, which depends on users satisfaction. This satisfaction is affected by the gain perceived by users, the popularity of the media service, and the cache allocation. Cooperation between vehicles is used to calculate users satisfaction and also to decide the optimal upper and lower thresholds of the Media Service Counter (MSC) of each service. The MSC is defined to avoid using an explicitly utility function or mapping rule.

In VANETS cooperation between network nodes is not only used to increase the message delivery ratio. Hao et al. [52] proposed a cooperative message authentication protocol for urban scenarios. This protocol allows vehicles to share their verification results with each other, reducing the number of security messages that each vehicle needs to verify. In order to select verifiers in an urban scenario, three verifier's selection algorithms were proposed: n-nearest, most even distributed, and compound. Similar security approaches may be found in [53,54].

3. Delay and Disruption Tolerant Networks

This section overviews the main Delay Tolerant Networks (DTNs) concepts and focuses on the cooperation problem in DTNs presenting the most relevant proposals in this field. The DTN architecture [12] implements a store-carry-and-forward paradigm, which allows to interconnect regions that operate on different transmission media. To enable this important feature, DTNs overlay

the protocol layer, called bundle layer, above the transport layer. Contrary to traditional Internet, DTNs set a hop-by-hop session instead of an end-to-end communication path. This hop-by-hop session enables asynchronous message (i.e., bundle) delivery over physically environments characterized by disruption and long delays. This approach allows bundles to travel between two or more regions in order to reach its final destination.

DTN store-carry-and-forward paradigm exploits the high mobility of nodes to operate in the network. The operating process can be described as follows. A source node originates a bundle and stores it (using some form of persistent storage) until a contact opportunity is available. When this opportunity become available the bundle is forwarded to a node assuming that this node is closer to the destination node. This process will be repeated until the bundle reaches its final destination. The network environment has a huge impact on the contact schedule between network nodes [55]. DTN contacts may be classified as opportunistic, predicted, or scheduled. In opportunistic contacts, communications between nodes happen in an unexpected way and may occur at any point of the network. As nodes move along predictable paths, it is possible to predict time schedules for their future position in the network. Knowing time and position of a node allows communication sessions to be scheduled. Predicted contacts require an analysis of the previous contacts in order predict the next opportunity to transmit data.

Based on the above-presented types of contacts, several routing schemes were proposed for DTNs [55–57]. These routing protocols are deployed in DTNs according to the contact characteristics and the knowledge available about the network. In DTNs routing protocols may be divided as forwarding-based or flooding-based. Forwarding-based approaches use the available information on the network to forward bundles using the best path. Contrary to this approach, flooding-based approaches do not use any network information replicating bundles at each contact opportunity hoping that the other node find a path to the destination. By replicating bundles, this type of routing protocols overcome the performance of forwarding-base approach as they increase the bundle delivery probability and decrease the bundle delivery delay. In spite of its benefits, flooding-based approaches increase the consumption of network resources (e.g., bandwidth and storage), leading to a poor performance of the network [58]. The overall network performance can be improved through cooperation between network nodes. Next subsection highlights the most important contributions related to cooperation between network nodes in DTNs.

3.1. Cooperation mechanisms for Delay-Tolerant Networks

The performance and competence of DTNs are affected by limited storage capacity and limited network bandwidth [58,59]. Moreover, these problems are accentuated by long and variable delays, node density, node mobility, and disruption. To overcome these specific issues cooperation plays an important role. In cooperative environments, nodes collaborate with each other, storing and forwarding bundles not only in their only interest, but also in the interest of other nodes. This behavior increases the number of contact opportunities and the probability of bundles find a path to its final destination. In a non-cooperative scenario, nodes will act as selfish nodes. This behavior may be caused by resources constraints (e.g., limited store capacity and energy) or just as a malicious behavior. A malicious behavior performed by certain nodes may lead to network performance degradation. Summarily, cooperation between nodes is highly important because it improve the limited capability of nodes and consequently improves the overall network performance.

In [60], the authors states that DTN routing protocols assumes a fully cooperative environment. This is an unrealistic assumption

since network nodes may be unable to cooperate due to resource constraints, to a common strategy, or to a selfish behavior. In this work, mechanisms to handle with uncooperative nodes are not presented. However this work presents several conclusions about the impact of cooperation mechanisms in the performance of DTNs. One of these conclusions is that algorithms that considered cooperation mechanisms perform better under cooperative scenarios than in non-cooperative ones.

Buttyán et al. [61] proposes a new mechanism that tries to encourage nodes to have a cooperative behavior during a message exchange. This mechanism takes several contributions from a game-theory model. Performance evaluation studies show that with this cooperative mechanism implemented in each node contributes to an improvement of the overall network performance. Another performance study of DTNs where nodes have a malicious behavior is presented in [62]. This study confirms that when nodes have a selfish behavior, the overall network performance decrease. In this work is also proposed a scheme to stimulate cooperation between nodes. This scheme uses pair-wise tit-for-tat (TFT) incentive mechanism. TFT assumes that every node forwards as much traffic for a neighbor as the neighbor forwards for it.

Cooperative ARQ scheme (C-ARQ) [63] were proposed as a new approach to stimulate cooperation in DTNs. This scheme tries to reduce packet losses in transmissions between fixed access points placed along roads and passing-by vehicles. Vehicles cooperate between them in order to enable communications in areas where there is no connectivity to access points. The same authors propose other cooperative scheme called DC-ARQ (Delayed Cooperative ARQ) [64]. The main difference between these two schemes is that in C-ARQ cooperation occurs in a packet-by-packet basis and in DC-ARQ the cooperation waits until vehicles are out of range of the access point. A framework that makes use of two cooperation mechanisms is proposed in [65]. These framework is based on the work presented in [64] and uses it to reduce the number of packets losses during communications between network nodes. This scheme also predicts nodes trajectory, which in conjunction with the store-carry-and-forward paradigm is used to improve the overall network performance.

In [66], the effects of different layers of node cooperation between nodes in DTN routing protocols are evaluated using a theoretical framework. The performance studies in this work are split into three parts. The first one studies how Epidemic [67] and Two-Hop [68] performs in terms of delivery probability when a fully cooperative environment is assumed. Afterwards, the Epidemic routing protocol is deployed in environments with different layers of cooperation. Finally, a simulation study is performed using Epidemic, Two-Hop, and Binary version of Spray-and-Wait [69] under multiple layers of cooperation. In the conducted studies Binary version of Spray-and-Wait has the best performance, since it presents a better flexibility to lower node cooperation.

Altman [70] uses Two-Hop routing protocol to study the impact of cooperation in DTNs. In this study nodes compete with each other using a game theoretical scheme. A set of equilibrium policies is enforced in order to compare cooperative and non-cooperative scenarios. In [71], the authors present a new concept, called “resource hog”. In this concept a DTN node tries to send more of its own data and possibly forward less peer data than a typical well-behaved node. Also “resource hog” nodes may have a malicious behavior and accept all incoming messages sent by peer nodes, but immediately drop them. Simulation studies prove that the performance of well-behaved nodes drops in the presence of nodes acting as resource hogs.

4. Vehicular Delay-Tolerant Networks

This section is dedicated to Vehicular Delay-Tolerant Networks (VDTNs) main features and how cooperation should be used in order to improve the overall network performance. VDTNs appear as a novel approach for vehicular networks by gather some important contributions from DTNs and Optical Burst Switching (OBS) [72]. The VDTN architecture is mainly characterized by the separation of the control and data planes, and by placing the bundle layer below the network layer. This approach enables the introduction of an IP over VDTN approach, which allows large messages to be routed instead of small IP packets. With this approach fewer routing decisions will be taken, which results in less complexity, lower cost and energy savings.

The VDTN control plane is performed using a low power and low bandwidth, to set a long-range link, which is always active to allow node discovery. On the other hand, VDTN data plane uses a high-power and high bandwidth to set a short-range link. This short-link is only active during the estimated contact duration time, if there are data bundles that should be exchanged between network nodes [13,73]. Otherwise, the data plane link connection is not activated. This approach is very important because it not only ensures the optimization of the available data plane resources (e.g. storage and bandwidth), but also allows power savings, which is very important for energy-constrained network nodes such as stationary relay nodes [13,74]. These nodes are usually power-limited since they may run on solar panels or batteries. In VDTNs three different types of nodes are considered: terminal, relay, and mobile. Terminal nodes may be fixed or mobile devices that act as messages (bundles) source and destination nodes. Usually, if a terminal node is a fixed device, it is placed at the edge of the VDTN network. One or more terminal nodes may have direct access to the Internet. Relay nodes are stationary nodes, placed at crossroads, with store-and-forward capabilities. They are used to increase the number of contact opportunities. Finally, mobile nodes are exploited in order to implement the store-carry-and-forward paradigm. An example of the interaction between VDTN network nodes may be the following: at the time $t + t_0$, a mobile node and a relay node detect each other and start exchanging signaling messages and routing information through the control plane link connection. Both nodes use routing information to determine which bundles should be forwarded. Then, the data plane connection is configured and activated on both nodes at the time $t + t_1$. Bundles are exchanged until the time $t + t_2$. After this time instant data plane connection is deactivated, since nodes are no longer in the data plane link range of each other.

To deploy the store-carry-and-forward paradigm, mobile nodes move along roads, storing and exchanging bundles with other network nodes. However, the high mobility of vehicles leads to short contact durations that limit the amount of data to be transferred. If we take into account that the amount of data is already limited due to bandwidth and transmissions ranges, short contact durations contributes to a decrease of the overall network performance. In addition, physical obstacles and interferences also affect the overall network performance. Subsequently, this comprehends the strategies for signaling and resources reservation (e.g., storage and bandwidth). To perform VDTN out-of-band signaling cooperation between networks nodes is required. Next subsection overviews the most important techniques to enforce cooperation in VDTNs.

4.1. Cooperative techniques for Vehicular Delay-Tolerant Networks

In order to improve the overall network performance, VDTNs may follow the same approach used for VANETs and DTNs. Nodes should be encouraged to have a cooperative behavior and share

Table 1
Summary of different kinds of cooperative proposals and their features for MANETs.

Authors' name	Characteristics			Evaluation platform
	Proposal approach	Conceptual characteristic	Optimization	
S. Buchegger and J.Y.L. Boudec, 2003.	Reputation-based approach	<ul style="list-style-type: none"> • Employ neighbourhood watch. • Share information about malicious behaviour of nodes and learn from them. 	<ul style="list-style-type: none"> • Reputation system with network alarms. 	Simulation
S. Bansal and M. Baker, 2003.	Reputation-based approach	<ul style="list-style-type: none"> • Direct first-hand observations of other nodes' behaviour. • Encouragement of proper routing participation. 	<ul style="list-style-type: none"> • Consider two types of routing misbehaviour: misleading and selfish. • Implementation of five components: Neighbour Watch, Route Ranker, Ranked-based routing, Malicious Traffic Rejection, and Second Chance Mechanism. 	Simulation
T. Anantvalee and J. Wu, 2007.	Reputation-based approach	<ul style="list-style-type: none"> • Introduction of a new type of node called a suspicious node. • Use a reputation management system. 	<ul style="list-style-type: none"> • Implementation of a state model to decide what should be done in response to nodes in each state. • Use of a timing period to control when the reputation should be updated. 	Simulation
S. Misra et al., 2012.	Reputation-based approach	<ul style="list-style-type: none"> • Use Learning Automata (LA) to optimize the selection of paths by avoiding faulty nodes. • Introduction of a "goodness value" that is increased each time a packet is successfully forwarded and decreased each time a packet delivery failure is detected. 	<ul style="list-style-type: none"> • The learning process is executed at each node and the collective orchestration of the process at all the nodes determines the performance of the overall system. • If an existing link fails, alternative routes can be determined based on the goodness values. 	Simulation
S. Sukumaran and V. Jaganathan, 2010.	Reputation-based approach	<ul style="list-style-type: none"> • The best possible route between two network nodes is calculated. • A reputation mechanism is used to identify selfish nodes. 	<ul style="list-style-type: none"> • Employment of a monitoring mechanism that helps to find out the reputation value of the neighbouring nodes. 	Simulation
C. Chen and S. Kishore, 2011.	Pricing-based approach	<ul style="list-style-type: none"> • Explore the fact that cooperation is beneficial when users' channel conditions are distinct. • Applies the concept of "valuable cooperation", which means one node with a good channel helps to relay the packet of a user who suffers from a poor channel. 	<ul style="list-style-type: none"> • Proposal of a two-user cooperation model. 	Simulation
D. Mathews et al., 2008.	Pricing-based approach	<ul style="list-style-type: none"> • All network nodes start to be selfish until they receive some payment rewarding their cooperative behavior. • Proposal of a QoS route model for communications between nodes. 	<ul style="list-style-type: none"> • Proposal of a pricing scheme that rewards the source, the relays and the destination nodes. 	Simulation

their resources with each other. The VDTN architecture defines network functions based on cooperation between nodes. When nodes perform the control plane, they exchange information such as geographical location, current path, or velocity. The exchanged of this information in a cooperative way, allows the prediction of time that data plane links will be available in a communication between nodes [73]. With this cooperative behavior nodes data link connections can be configured to be active only during that time.

This approach allows nodes to save power, which is an important resource for nodes with limited energy resources. Besides, by knowing the time that links are available, it is possible to calculate the maximum number of bytes that can be exchanged during a contact opportunity. This important concept improves the data plane link performance, since it will be possible to avoid incomplete data bundle transmissions and consequently the waste of link capacity [75]. As VDTNs uses control plane to exchange informa-

tion, cooperative exchange of signaling information may also be a useful tool that can be used to accept or deny a contact opportunity. A contact opportunity must be denied if a node has energy constraints, if the contact duration is not enough to transmit a complete bundle, or even if a node buffer does not have enough space. This cooperative approach allows bundles from being dropped and decreases power consumption. This approach also enables the exchanged of any kind of information (e.g., routing state information or bundle delivery notifications) and uses it to improve the overall network performance.

Cooperation in VDTNs may also be adopted at the data plane level. Nodes exchange bundles between a source and a destination node. However, each time a node establishes a connection they have to deal with limited data plane resources, such as storage and link bandwidth. In such conditions an unconditionally store capacity cannot be taken as granted. This also severely limits the

Table 2
Summary of different kinds of cooperative proposals and their features for VANETS.

Authors' name	Characteristics			
	Proposal approach	Conceptual characteristic	Optimization	Evaluation platform
T. Chen et al., 2011.	Incentive-based approach	<ul style="list-style-type: none"> Based on coalitional game theory to solve the forwarding cooperation problem. Ensure that whenever a message needs to be forwarded in a VANET, all involved nodes have incentives to form a grand coalition. 	<ul style="list-style-type: none"> Proposal of an incentive scheme that takes into consideration the limited storage space of each node. Lightweight approach that makes full use of the selfishness of the autonomous nodes, giving them the freedom to choose which messages to discard. 	Simulation
F. Dotzer et al., 2005.	Reputation-based approach	<ul style="list-style-type: none"> Three different areas are distinguished: event area, decision area, and distribution area. Each time a message is distributed every forwarding node appends its own opinion about the message's trustworthiness. 	<ul style="list-style-type: none"> Design of a reputation system for very large vehicular ad hoc networks. Introduction of direct and indirect trust as well as opinion piggybacking to enable confidence decisions on event messages. 	Simulation
P. Caballero-Gil et al., 2010.	Incentive-based approach	<ul style="list-style-type: none"> Nodes are rewarded depending on their behaviour. Incentives are defined by a convex function. 	<ul style="list-style-type: none"> To reward nodes, authors consider several parameters, such as packet delivery deadline, number of forwarding's, or distance between source and destination nodes. 	Simulation
Z. Wang and C. Chigan, 2007.	Trust-token based approach	<ul style="list-style-type: none"> Symmetric and asymmetric cryptography mechanisms are considered to protect packet integrity. Only intentional misbehaviour nodes are considered. 	<ul style="list-style-type: none"> Proposal of a Dynamic Trust-Token (DTT) based cooperation enhancement mechanism. Use Neighborhood WatchDog to generate Trust Token based on instant performance to verify packet correctness. 	Simulation
M. Jerbi et al., 2009.	Reputation-based approach	<ul style="list-style-type: none"> Information about vehicular traffic density and the road topology to efficiently relay data in the network is considered. Each vehicle in the network knows its own position and speed using GPS. 	<ul style="list-style-type: none"> Proposal of the improved greedy traffic-aware routing protocol (GyTAR). 	Simulation
L. Zhou et al., 2011.	–	<ul style="list-style-type: none"> Distributed media service scheme in Peer-To-Peer (P2P) based vehicular networks, which depends on users satisfaction. Aims at achieving maximal user satisfaction and certain fairness by jointly considering media-aware distribution and opportunistic transmission. 	<ul style="list-style-type: none"> Distributed media-service scheme that jointly solves the content dissemination, cache update, and fairness problems for P2P-based vehicular networks. 	Simulation
M. Li et al., 2011.	Reputation-based approach	<ul style="list-style-type: none"> Symbol level network coding (SLNC) is used to combat the lossy wireless transmissions. Messages are forwarded only for nodes with a reputation score above the pre-defined threshold. 	<ul style="list-style-type: none"> Proposal of CodeOn, a high-rate cooperative PCD scheme for vehicular networks. Performs network coding on finer granularity of physical layer symbols. 	Simulation
Y. Hao et al., 2012.		<ul style="list-style-type: none"> Each safety message carries the location information of the sending vehicle. Verifiers of each message are defined according to their locations in relation to the sender. 	<ul style="list-style-type: none"> Proposal of cooperative message authentication protocol (CMAP). Definition of three verifiers' selection algorithms, n-nearest method, most-even distributed method. 	Simulation

transmission of other bundles due to short-lived links and finite bandwidth. Soares et al. [76] studied the cooperation problem in VDTNs. Performance studies enforce cooperation on control plane, and shows that cooperative exchange of signaling messages helps to improve the overall network performance. This studies uses node location information to accept or deny a contact opportunity.

The same study also focus on the cooperation problem at the data plane link. To do such work, authors assume that nodes resources are divided into two parts. The first part is reserved to store and forward bundles to other node, while the second part is used for cooperation purposes. The presented results shown that this approach presents considerable gains to the results presented in [73].

Table 3
Summary of different kinds of cooperative proposals and their features for DTNs and VDTNs.

Name of authors	Characteristics			Platform
	Proposal approach	Conceptual characteristic	Optimization	
L. Buttyan et al., 2007.	Pricing-based approach	<ul style="list-style-type: none"> • A game-theoretic model is considered to stimulate cooperation between nodes. • This model assumes that the communication cost is higher than the storage cost, and messages lose their value over time. 	<ul style="list-style-type: none"> • Proposal of a mechanism to discourage selfish behaviour based on the principles of barter. • The efficiency of the social optimum with respect to Nashia equilibria is considered. 	Simulation
U. Shevade et al., 2008.	Incentive-based approach	<ul style="list-style-type: none"> • Use a game-theory principle. • During a message exchange nodes are incentive to cooperate. 	<ul style="list-style-type: none"> • Proposal of a practical incentive-aware routing scheme based on the TFT mechanism for selfish users to optimize their own performance without significant degradation of system-wide performance. 	Simulation
J.M. Pozo et al., 2008.	–	<ul style="list-style-type: none"> • Cooperation among cars is established in the dark areas, where connectivity with the APs is lost. • Three distinct phases are considered: association, reception, and cooperative-ARQ. 	<ul style="list-style-type: none"> • Propose of a variation of the Cooperative ARQ (C-ARQ) scheme to be used in vehicular networks where cars download delay-tolerant information from APs on the road, suffering an intermittent connectivity. 	Real Environment
O.T.-Cruces et al., 2009.	–	<ul style="list-style-type: none"> • Use a DC-ARQ mechanism to reduce packet losses of transmissions from AP to vehicles and from vehicles to vehicles. • Use a carry-and-forward mechanism based on the predictability of vehicle road routes that cross opportunistically other vehicles to improve transfer delivery of information. 	<ul style="list-style-type: none"> • Definition of a Vehicular Ad Hoc Network framework following a DTN architecture that opportunistically allows downloading packets when vehicles cross AP. 	Real Environment
J. Dias et al., 2013.	–	<ul style="list-style-type: none"> • Two layers of cooperation are defined: one at the control plane, other at the VDTN data plane. 	<ul style="list-style-type: none"> • Proposal of four different cooperation mechanisms for VDTNs. Two of them based on nodes performance. 	Simulation
J. Dias et al., 2013.	Reputation-based approach	<ul style="list-style-type: none"> • The network has a pre-defined threshold that is used to classify nodes. • Nodes with a reputation score below the threshold are marked as misbehavior nodes and added to a black list. 	<ul style="list-style-type: none"> • Proposal of a reputation system with four different approaches to detect and isolate selfish nodes. 	Simulation

Another study about the impact of cooperation mechanisms in VDTNs is presented [77]. This study focuses on the impact of cooperation mechanisms in the most commonly used routing protocols in VDTNs. Taking into consideration the above-presented study, four different cooperation strategies were presented in [78] and their impact on the performance of VDTNs were evaluated. The first strategy, called Static Mandatory Cooperation (SMC) forces all network nodes to cooperate with a pre-defined cooperation percentage. This strategy also ensures that all network nodes cooperate with the same percentage. Similar to this approach, the authors propose the Random Mandatory Cooperation (RMC). The main difference between these two approaches is that in RMC the percentage that nodes cooperate in a contact opportunity is randomly chosen. The other two approaches takes into consideration the node performance to choose the cooperative percentage of each node. For example, the Node Performance Cooperation (NPC) calculates the ratio between the number of sent and received messages. A node with a higher cooperative percentage is a node that sends more messages than the ones it receives. Simulation studies were conducted using the VDTNsim tool [79], which is an extension of the ONE simulator [80,81] and allows simulating the

VDTN architectural approach. A real map of Serra da Estrela region were considered with 25 terminal nodes placed at real-world sparse villages. Four different scenarios with 5, 10, 15, and 30 cooperative mobile nodes are considered, using Epidemic and Binary Spray-and-Wait routing protocols. It was shown that the proposed approaches contribute to the improvement of the overall network performance.

More recently, a reputation system for VDTNs were proposed [82], which main goal is to provide a tool that allow network nodes to avoid contacts with selfish nodes in order to optimize the overall network performance. In order to accomplish such goal four different reputation approaches were implemented to detect, identify and avoid communications with selfish nodes. These four approaches takes into consideration nodes behavior and their reputation score. To reward nodes, schemes increase nodes reputation each time a bundle is successfully delivery to its final destination. Each time a node drops a bundle without sent it at least once, schemes decrease this node reputation score. Each node also maintains a blacklist containing all nodes with a reputation score below a pre-defined cooperative threshold. This will allow nodes to save resources by ignoring contact requests from the blacklist nodes.

Using the same simulation tool used in [78] and a map-based model representation of Dakar region in Senegal, 27 real world medical clinics were considered to place VDTN terminal nodes that act as traffic sources. Using 100 vehicles and five different reputation thresholds, conducted studies have shown that schemes that punish nodes in a more aggressive way contribute to an increase of the bundle delivery probability and consequently to the decreasing of the bundle average delivery delay.

5. Discussion and open issues

The effective operation of vehicular networks depends on the cooperation between network nodes. In DTNs and VDTNs cooperation plays a key role because such networks implements a store-carry-and forward protocol, which depends exclusively on cooperation nodes. Most of the research studies presented up to now assume fully cooperative network architecture. However, this is an incorrect assumption because nodes may be unwilling to cooperate in order to preserve their resources (e.g. energy, storage space, data integrity). Thus, nodes can have a selfish behavior and consume resources contributed by other nodes without paying with any resources in return.

Tables 1, 2, and 3 provide a summary and offer a comparison analysis between the above-described cooperative solutions for wireless ad-hoc and vehicular networks. Moreover, these tables highlight the classification of each solution into specific categories.

After a detailed analysis of the most recent cooperation techniques for vehicular networks, the following open issues can be identified and suggested:

- **Synchronization and Security:** Cooperative systems require extra security and synchronization, which can be a very challenging task. Although research efforts have been made on security issues in vehicular networks, in general, and particularly security on existing cooperative routing protocols, some challenges can still be addressed.
- **Complex Schedulers:** Systems using multiple nodes relaying information between each other requires more sophisticated schedulers. These schedulers should determine in an accurate way the best nodes to cooperate in order to achieve an optimum relaying. This can be a hard task due to the presence of selfish node and uncooperative nodes.

6. Conclusion

Vehicular networks are emerging as a possible solution to enable communications where a path between the source and destination may not be available. However, this type of networks has several issues (e.g., storage capacity, limited power, or transmission ranges) that must be solved in order to improve the overall network performance. A possible solution to solve some of these issues is to stimulate nodes to cooperate among them. Many different cooperation approaches have been proposed in the literature not only to stimulate cooperation between nodes but also to identify and isolate selfish nodes.

This work summarizes the most important projects, frameworks, and proposals about node cooperation in vehicular communications. Such networks may gather several contributions from wireless ad-hoc networks. Most of the proposed schemes for these networks rely on two main approaches: reputation-based and pricing-based. At reputation-based approaches, cooperative nodes are rewarded by increasing their reputation score in the network, while selfish and misbehavior nodes are punished and eventually prohibited from receiving messages. Contrary to this approach, in pricing-based approaches, nodes are paid for their cooperative behavior. Both approaches are also considered to create cooperation

strategies for VANETs, DTNs, and VDTNs. Vehicular networks also introduce a new type of cooperative approaches based in trust tokens to identify and isolate selfish nodes. Several routing strategies for vehicular networks were also proposed basing its principles on cooperation between nodes.

The studies already conducted show that vehicular networks present significant gains in terms of performance when nodes are stimulated to cooperate. It is also important to notice that malicious behavior of uncooperative nodes may contribute to the decrease of the overall network performance. In order to minimize the effect of such nodes in the network, the rewards that nodes receives when cooperate in a communication should be carefully studied.

This work may be used as a base to propose more complex reputation strategies and schedulers that contributes to increase of the overall network performance.

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Chapter 3

The Impact of Cooperative Nodes on the Performance of Vehicular Delay-Tolerant Networks

This chapter is based on the following paper:

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João A. F. F. Dias, Joel J. P. C. Rodrigues , João N. G. Isento, and Jianwei Niu

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The Impact of Cooperative Nodes on the Performance of Vehicular Delay-Tolerant Networks

João A. F. F. Dias · Joel J. P. C. Rodrigues ·
João N. G. Isento · Jianwei Niu

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Abstract Vehicular communications refer to a wide range of networks proposed for environments characterized by sparse connectivity, frequent network partitioning, intermittent connectivity, long propagation delays, asymmetric data rates, and high error rates. These environments may also be characterized by a potential non-available end-to-end path. To overcome these issues and improve the overall network performance, cooperation between network nodes must be severely considered. Nodes may cooperate by sharing their storage capacity, bandwidth, or even energy resources. However, nodes may be unwilling to cooperate due to a selfish behavior or to an intent to protect the integrity of their own resources. This selfish behavior significantly affects the functionality and performance of the network. This paper overviews the most recent advances related with cooperation on vehicular networks. It also studies the impact of different cooperation levels in the performance of Vehicular Delay-Tolerant Networks (VDTNs). It was shown that scenarios with a higher number of cooperative nodes present the best results in terms of bundle delivery delay.

Keywords Vehicular networks · Vehicular Ad-Hoc networks · Delay-tolerant network · Vehicular delay-tolerant network · Cooperation · Performance evaluation

J. A. F. F. Dias · J. J. P. C. Rodrigues (✉) · J. N. G. Isento
Instituto de Telecomunicações, University of Beira Interior,
Covilhã, Portugal
e-mail: joeljir@ieee.org

J. A. F. F. Dias
e-mail: joao.dias@it.ubi.pt

J. N. G. Isento
e-mail: joao.isento@it.ubi.pt

J. Niu
School of Computer Science and Engineering, Beihang University,
Beijing, China
e-mail: niujianwei@buaa.edu.cn

1 Introduction

Vehicular communications have been the focus of several studies conducted by the scientific community and the automotive industry. In a vehicular environment, vehicles must be equipped with short-range wireless devices in order to communicate with other vehicles or with roadside infrastructure equipment [1–3]. Enabling communications between vehicles allow deploying a large number of scenarios containing different applications and services [2–4].

Although the large number of already-conducted studies, vehicular networks still face numerous challenges that should be overcome. Most of these challenges arise from the high mobility and speed of vehicles. For example, the network topology changes constantly leading to intermittent connectivity and significant loss rates, which may also be caused by limited transmission range, radio obstacles and interferences. Despite the above-presented issues, researchers face enormous challenges, such as the lack of an end-to-end path between source and destination.

Several vehicular network architectures are proposed to overcome the above-presented issues, such as Vehicular Ad-Hoc Networks (VANETs) [1–6], Delay-Tolerant Networks used on vehicular networks environments [7], and Vehicular Delay-Tolerant Networks (VDTNs) [8]. VANETs are a subset of Mobile Ad-Hoc Networks (MANETs) [9–11] where vehicles are exploited as mobile nodes in order to enable communications between network nodes. In VANETs, vehicles may communicate with each other establishing Vehicle-to-Vehicle (V2V) architecture. Vehicles may also communicate with roadside infrastructures establishing Vehicle-to-Infrastructure (V2I) architecture. A hybrid architecture combining both approaches may also be considered. Independently of the chosen architecture, VANETs assume the existence of an end-to-end path. However, this type of network is not able to deal with network partition, disconnection and long time delays.

Later, DTNs appeared as a possible solution to overcome VANETs problems. In order to achieve this goal, a store-carry-and forward paradigm is deployed. This paradigm, in a vehicular communications scenario, may be described as follows. A vehicle moving along roads is able to communicate with other vehicles. This vehicle stores data until a contact opportunity is available. When a contact opportunity is available, data is forwarded using a specific routing protocol. This process is repeated until data reaches its final destination.

Recently, VDTNs were proposed as another solution for vehicular networks. They consider three node types: terminal, relay, and mobile nodes. Terminal nodes are usually placed at the edge of the VDTN network and are responsible for message (bundle) aggregation and de-aggregation. Relay nodes are placed at crossroads and are responsible to increase the number of contacts between network nodes, storing bundles until a promising contact opportunity occurs in order to carry the bundles closer to their destination node [12]. Mobile nodes move along roads and may interact with all VDTN node types. These nodes may also act as terminal nodes. VDTNs get several contributions from DTNs, such as the store-carry-and-forward paradigm with the of control and data planes separation (performing out-of-band signaling).

Although the already conducted studies vehicular networks still presents a large number of challenges that should be overcome. One open issue in vehicular networks is cooperation between network nodes. Enforcing cooperation in such networks is not an easy task and presents a large number of technical challenges. In order to cooperate, nodes shall be afforded with sophisticated schedulers. Otherwise, cooperative systems require that nodes are able to determine which node is the best node to cooperate. This is not an easy task since nodes may be characterized by a selfish or uncooperative behavior. It is very important to study the best way to stimulate nodes to cooperate in order to create cooperative systems that provide an optimal quality of service (QoS), with potential performance gains without compromising or deteriorating the network performance.

This paper presents a detailed study about the influence of cooperative nodes in the performance of VDTNs when deployed in a rural environment. To overview the impact of cooperation, nodes are required to share a percentage of their resources for the benefit of other. Different percentages of sharing are considered and impact of uncooperative nodes in the performance of the overall network is also studied. Then, the main contributions of this paper are the following:

- A review of the state of the art considering the most relevant contributions on network cooperation for vehicular networks;
- Proposal of two levels of cooperation for VDTNs, considering buffer space and connection-time sharing;

- Exhaustive studies in order to evaluate the network performance improvement by applying cooperation strategies on VDTN nodes, considering the most relevant routing protocols.

The remainder of this paper is organized as follows. Section 2 focuses on the cooperation problem and details the state of the art on cooperation in vehicular networks. Section 3 describes the VDTN architecture and how cooperation may be enforced in such networks, while Section 4 presents the performance assessment analysis of cooperation in VDTNs. Section 5 concludes the paper providing a final summary of the study and suggestions for further works.

2 Related work

When a vehicular network is deployed in a particular region it is important to keep in mind that a routing protocol with a good performance is not enough to ensure a good network performance. In such networks, it is very important to guarantee that all nodes follow the selected routing protocol. This problem takes special attention when two types of nodes are considered: selfish and cooperative. Selfish nodes may belong to individual users that are unwilling to forward messages from other users. This may occur due to the fact of carrying messages from others forces these individual nodes to share they own resources (e.g., storage space, power). Therefore, sharing resources with other nodes in exchange of nothing does not become appealing. Furthermore, a cooperative node is a node with high mobility inside the network, which results in a higher probability to encounter other network nodes. These types of nodes (e.g., cars, trucks, taxis, and buses) are usually picked as messages forwarders. In spite of these nodes are able to cooperate, they should take into account that cooperation causes the overwhelming load of services for other nodes. This results in a higher consumption of resources (e.g., bandwidth, storage space, energy) that will lead nodes to diverge from the protocol in order to save their own data or resources.

To stimulate cooperation between network nodes it is very important to offer them incentives for cooperation. For example, in MANETs two types of incentives are considered, reputation-based [13–17] and credit-based [18, 19]. In reputation-based approach, nodes take into account the behavior of their neighbors in order to give them a reputation. If a node is marked as a non-cooperative node this node will be punished. On the other hand, in the credit-based approach, nodes collect credits as a reward of their cooperative behavior. This type of approaches is highly considered in vehicular networks. However, they cannot be directly applied since an end-to-end path is not ensured.

In VANETs, several schemes and systems were already proposed to deal with cooperation between network nodes.

Chen et al. [20] proposes a scheme where a node is rewarded each time it cooperates with another one. By given them this incentive it was shown that nodes follow rigorously the established routing protocol. In order to preserve the best interests of each node this scheme considers storage space limitations. This scheme is based on coalitional game theory.

Vehicle Ad-Hoc Network Reputation System (VARS) [21] was proposed to enforce cooperation in VANETs. This system is based on the concepts *opinion generation* and *confidence of the decision*. With this system, each time a message is exchanged between two nodes, the receptor generates an opinion on the trustworthiness of this message. This opinion is calculated considering three different approaches. It can be calculated using other nodes partial opinions that are attached to the message, using indirect trust (if the sender is known), or a combination of both. Calculated the node opinion, this is attached to the message the next type it is forwarded. The confidence decision is calculated by verifying the constraints based on the node reputation levels.

In order to stimulate the cooperation between VANET nodes, in [22], authors propose a new scheme. This scheme rewards all the intermediary nodes that participate in the forwarding process of a specific message. In order to accomplish it, each time a message reaches its destination, all the participant nodes should report its contribution to the source node. By reporting nodes participation to the source node allows source node to calculate the final contribution of each node. This contribution is calculated through the sum of the partial contribution given by each node in the forwarding tree. Each intermediate node will receive a percentage as a reward for forwarding the message.

Wang et al. [23] propose a dynamic trust-token (DDT) based on cooperation enhancement mechanism. With this scheme, selfish nodes are detected and marked as uncooperative nodes in order to notify other nodes. This approach ensures data packet integrity during the delivery process. Data packets are forwarded with a token attached in order to evaluate their correctness. To accept a packet, nodes will evaluate this token in order to prove their corresponding. During the network operation a reputation system of each node is set up.

In [24] authors propose a new protocol called Network Coding-based Medium Access Control for VANETs. This protocol takes advantages of cooperative Automatic Repeat reQuest (ARQ) techniques in order to minimize the number of total transmissions needed to deliver messages to their final destination. This is achieved by coordinate the channel access among a set of relays capable of using network coding.

The performance of DTNs is affected by several constraints such as limited network bandwidth, limited storage capacity, node density, or even disruption [25, 26]. To overcome these issues and improve the overall network performance, cooperation between nodes must be considered. The store-carry-and-forward paradigm of DTN architecture assumes that nodes

cooperate between them. DTN nodes are capable to store and forward bundles, not only in their own interest, but also in the interest of other nodes. Using this approach, the number of contacts opportunities increase, which result in a considerable improvement of the network performance.

Panagakos et al. [27] state that DTN routing protocols must assume a fully cooperative environment in order to improve the overall network performance. This is not a correct and consistent assumption because network nodes may adopt a selfish behavior due to resource constraints or strategy. However, this work studies the impact of cooperation in the following three well-known routing protocols: Epidemic [28], Two-hop [29], and Spray-and-Wait [30]. It was shown that cooperative algorithms perform better than uncooperative ones. In this work authors also include simple cooperation mechanism, which proved to improve the overall network performance. Authors of [31] propose a game-theory mechanism to stimulate cooperation between nodes. Performance experiments show that, individually, the most beneficial behavior leads to an improved social optimum system.

C-ARQ [32] is a cooperative scheme to stimulate cooperation between nodes in DTNs. The main goal of this scheme is to reduce packet losses during transmissions between vehicles and fixed access points. Cooperation is used to enable communications in places where an access point is not available. The same authors proposed a variant of C-ARQ called DC-ARQ (Delayed Cooperative ARQ) [33]. In this variant, cooperation between vehicles is active until they are out of range of the access point.

Taking into account the work presented in [33], Trullols-Cruces et al. [34] create a framework that considers two cooperation mechanisms. This framework tries to reduce the number of packet losses during vehicle communications. To accomplish this goal this framework calculates and predicts nodes trajectory. This feature combined with the DTN store-carry-and-forward paradigm improves the overall network performance.

Resta et al. [35] studied and evaluated the impact of different levels of cooperation in three DTN routing protocols. This study is conducted through a theoretical framework. In a first moment, Epidemic and Two-Hop schemes were studied assuming a fully cooperative environment. In this case, Epidemic overcomes the performance of Two-Hop. Thus, different layers of cooperation are enforced into Epidemic. To conclude this study, authors enforce the same cooperation layers into the binary version of Spray-and-Wait. Between all the conducted studies, binary version of the Spray-and-Wait routing protocol was the one who got the best results. In [36] the Two-Hop routing protocol was used to study the impact of node cooperation in DTNs. To stimulate nodes to cooperate, a game theory scheme was used. To compare a cooperative with an uncooperative scenario several balanced policies were used.

Solis et al. [37] present the “resource hog” concept. In this concept, nodes try to send more of their own data and less peer

data than a well-behaved node. This type of node may also act as a false cooperative node. They accept all the incoming messages, but discard them immediately. Several studies were conducted through simulation and it was shown that misbehaving nodes influence the performance of well-behaved nodes.

Despite of VDTNs being a recent vehicular architecture, cooperation has already addressed. Soares et al. [38] studied cooperation problem in VDTNs considering urban scenarios. Once VDTNs uses control and data plane separation, two different approaches were conducted. In the first one, performance studies concluded that cooperation on control plane helps to improve the overall network performance. Cooperation at the control plane level may be performed by stimulate nodes to exchange signaling messages containing different information about nodes (e.g., node location). This information may be used to accept or deny a contact opportunity. The second approach focuses on cooperation enforced at the data plane level. At data plane, nodes are stimulated to share their own resources in favor of other network nodes (e.g., storage capacity). Performance studies showed that cooperation in data plane present considerable gains when compared to cooperation at the control plane.

This section summarizes the most relevant projects, frameworks, and proposals about node cooperation in vehicular networks. All of them may be used as starting point to develop new proposals for cooperation in VDTNs.

3 Cooperation in VDTNs

Vehicular Delay-Tolerant Networks (VDTNs) were proposed as a new solution for vehicular networks in order to overcome issues that cannot be overcome by other approaches. VDTNs gather several contributions from other networks, such as DTNs and Optical Burst Switching (OBS) [39]. As DTNs, VDTNs also assume a store-carry-and-forward paradigm that allows the creation of a hop-by-hop path between source and destination nodes. This is accomplished by exploiting the high mobility of mobile nodes (vehicles). Similar to OBS, VDTNs also consider an IP over VDTN approach, placing the bundle layer below the network layer, where IP packets are aggregated in large data packets, called bundles. Based on the OBS networks, VDTNs also use out-of-band signaling by separating the control and data planes. In control plane, two nodes exchange signaling information that is used to determine if is possible to schedule a contact and reserve resources for data exchange among the nodes. This information available at the setup message includes node type, speed, power and storage capacity, and even supported linked technology. If a contact opportunity is beneficial for both nodes, control plane is also responsible to reserve the needed resources for this contact opportunity and corresponding data exchange. Data plane is

responsible to consume the previous reserved resources in order to transport incoming packets from source to destination nodes.

As well as all the other vehicular network architectures, VDTNs also have several characteristics that have direct impact on the network performance. One of these issues is caused by the high mobility of mobile nodes. This mobility causes frequent changes on the network topology that leads to a network partition. Thus, the velocity of mobile nodes is responsible for a short contact duration between network nodes that constrains the volume of data to be transferred. Adding these constraints to an already restricted network in terms of bandwidth and transmission range makes cooperation between nodes an important issue to be studied in order to improve the overall network performance.

VDTNs assume cooperation between nodes at the control plane level, which is performed, for example, by exchanging node localization information among network nodes in order to predict the period of time that a contact opportunity is available. However, cooperation is not limited to control plane. It is very important to extend cooperation to the data plane level in order to maximize the usage of data link resources.

To improve the overall network performance and deliver bundles from source to destination, nodes must cooperate between them. Nevertheless, a fully cooperative environment cannot be taken for granted. Mostly, this is due to nodes limitations in terms of resources (e.g., storage capacity and link bandwidth). These resources constraints may force nodes to reject bundles sent by others, in order to save buffer space for their own bundles. However, cooperation in data plane is not restricted to store bundles from other nodes. A node may also be cooperative by sending bundles from others that are stored on its own buffer.

In this work, the impact of cooperation in VDTNs is studied using two levels of cooperation between nodes. First, cooperation is enforced at nodes buffer where nodes are forced to share a percentage of their buffer capacity to store bundles from other nodes. The second level of cooperation considers cooperation at the data plane. In this case, nodes are enforced to share a percentage of time at each contact opportunity to send bundles from other nodes. These two levels of cooperation are studied considering scenarios with different percentage of cooperative nodes.

4 Performance analysis of node cooperation

This section focuses on the performance analysis considering the impact of node cooperation on the performance of VDTNs. Following the above-presented cooperation approaches presented at the end of the last section, simulation studies were conducted using the VDTNsim simulator [40]. This simulation tool is an extension of the ONE simulator

[41, 42], and is used for modeling the behavior of the VDTN architectural approach. VDTNsim allows modeling the store-carry-and-forward overlay network below the network layer.

For performance analysis purposes nodes are enforced to cooperate with the same percentage for buffer space reserved for other nodes bundles and time of contact spent to send others bundles. For example, if a network node share 10 % of its buffer to store bundles from others, it also shares 10 % of time of a contact opportunity to forward bundles from other nodes. Next subsections present the considered network scenario and the performance studies.

4.1 Network scenario

For performance studies, a simulation scenario was set up using a real world map of Serra da Estrela region, Portugal (shown in Fig. 1). In this scenario, 25 mobile nodes move along roads and between fixed terminal nodes. When a mobile node reaches a terminal node, it randomly waits between 15 to 30 min. Afterwards, a new random terminal node is selected to be the next destination point. Mobile nodes speed ranges between 30 and 80 km/h. In all the simulation experiments, mobile nodes have a buffer capacity of 125 Mega Bytes (MB). Terminal nodes are placed at 25 real-world sparse village locations and have a buffer capacity of 250 MB. Each terminal node is simultaneously a traffic source and traffic sink. Terminal nodes generate bundles using a creation interval in the range of [15, 30] minutes. All bundles have an infinite time-to-live (TTL) and a size in the range of [500 KB, 2 MB]. Without

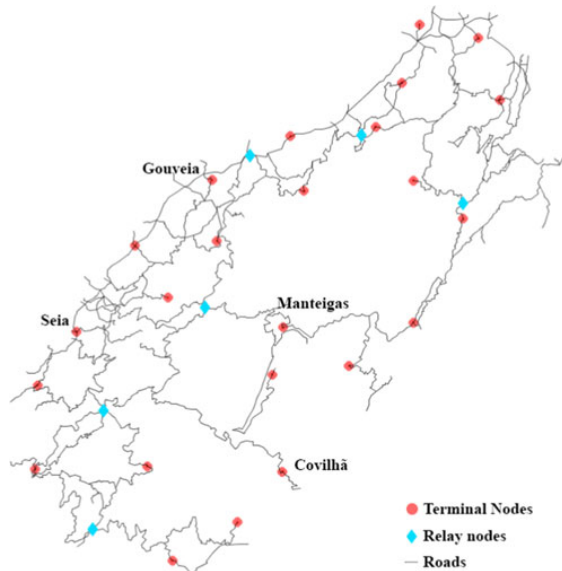


Fig. 1 Illustration of the Serra da Estrela region (Portugal) with the location of terminal and stationary relay nodes

a TTL, bundles are dropped in case of buffer congestion. To improve the number of contact opportunities, 6 relay nodes were place at crossroads with a buffer capacity of 500 MB. All network nodes use the standard IEEE 802.11b interface to communicate with other nodes and a data rate of 6 Mbps [43]. Nodes transmission range was set to 350 m.

For all the simulation experiments, the creation and exchanging of bundles is simulated for a period of 12 h. Four different scenarios with 100 %, 75 %, 50 %, and 25 % of cooperative mobile nodes are considered. For each scenario the performance of First Contact [44], Epidemic [28, 45], Spray and Wait [30], PRoPHET [46], and GeoSpray [47] routing protocols is evaluated.

Performance metrics considered in all the studies presented in this paper are the bundle delivery probability and the bundle average delivery delay. The bundle delivery probability (B_{DP}) is measured as the relation between the number of unique delivered bundles (U_{DB}) and the number of unique created bundles (U_{BC}), and it is shown on Eq. 4.1.

$$B_{DP} = \frac{U_{DB}}{U_{BC}} \tag{4.1}$$

The bundle average delivery delay (B_{AD}) is measured as the average time between bundles creation time and delivery. Equation 4.2 show how this metric is calculated. In this equation, T_D is the time when a bundle is delivered, while T_C is the time when the delivered bundle was created. T_{DB} is the total number of unique delivered bundles.

$$B_{AD} = \frac{\sum_{i=1}^{T_{DB}} (T_D - T_C)}{T_{DB}} \tag{4.2}$$

4.2 Impact of cooperation for first contact routing protocol

The first study considers the First Contact routing protocol. This protocol is a single-copy forwarding routing protocol that maintains at most one copy of a bundle in the entire network. Figure 2 shows the effect of the percentage of cooperative nodes on the bundle delivery probability. For each scenario, node cooperation percentage ranges from 10 % up to 90 %. As may be seen, a fully cooperative scenario (100 % of cooperative mobile nodes) increases the bundle delivery probability when compared to a scenario with 50 % or 25 % of cooperative nodes. More accurately, it present gains of approximately 1 %, 4 %, 5 %, 4 %, 4 %, 7 %, 7 %, 7 %, and 7 % (for node cooperation percentage equal to 10, 20, 30, 40, 50, 60, 70, 80, and 90%) when compared with a scenario with 50 % of cooperative nodes, and 2 %, 5 %, 7 %, 8 %, 9 %, 12 %, 12 %, 12 % and 12 % when compared to a scenario with 25 % of cooperative nodes. When compared to the scenario with 75 % of cooperative mobile nodes, the fully cooperative scenario only present gains when nodes share

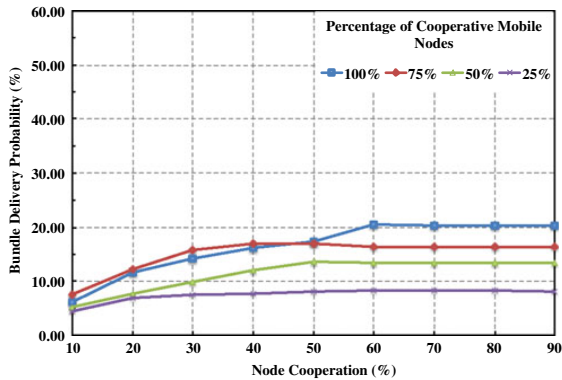


Fig. 2 Bundle delivery probability for First Contact routing protocol as function of the cooperation percentage for 25, 50, 75, and 100 % of cooperative mobile nodes

50 % or more of its own resources. In this case, the fully cooperative scenario present gains of 1 %, 4 %, 4 %, 4 %, and 4 % (for node cooperation percentage equal to 50, 60, 70, 80, and 90%). The main difference between these two scenarios is due to the increase of the contact time available to forward bundles from other nodes. Since First Contact is a single-copy routing protocol, as longer as nodes spend to forward bundles, higher is the probability of bundles reach its final destination. Enhancing this, a higher number of nodes that are able to cooperate contribute to a higher performance of the fully cooperative scenario.

Increasing the percentage of node cooperation it is expected that bundles stay at nodes buffer for a longer period of time. This will lead to an increase of the bundle average delivery delay. Thus, when the number of cooperative mobile nodes increase it also increase the number of hops needed to bundles reach their final destination. Consequently, this will further increase the bundle average delivery delay. This behavior can be observed in Fig. 3. It is even more evident when

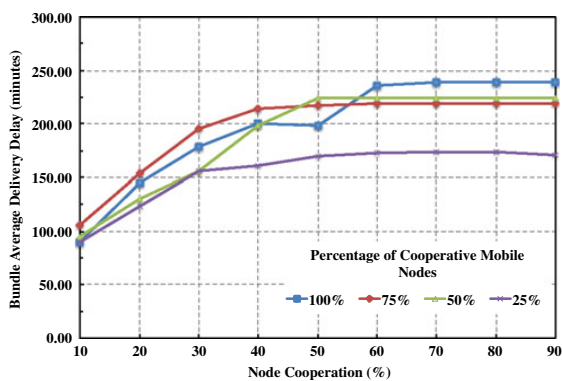


Fig. 3 Bundle average delivery delay for First Contact routing protocol as function of the cooperation percentage for 25, 50, 75, and 100 % of cooperative mobile nodes

nodes cooperate with 60 % or more of their own resources. When a fully cooperative environment is considered the bundle average delivery delay increases in 17, 20, 20, and 20 min (for node cooperation percentage equal to 60, 70, 80, and 90%) when compared to a scenario where 75 % of mobile nodes are able to cooperate. When compared to a scenario with 50 % of mobile nodes able to cooperate, the bundle average delivery delay increase in 12, 15, 15, and 15 min. Finally, when compared with the 25 % scenario the bundle average delivery delay increase in 63, 65, 65, and 68 min.

4.3 Impact of cooperation for epidemic routing protocol

Contrary to First Contact, Epidemic routing protocol is a multiple-copy routing protocol. This means that each time a bundle is forward to a node, the sender node keeps a copy of this bundle in its buffer until the bundle is discarded by buffer congestion. As expected, Epidemic performs better than First Contact presenting better delivery probabilities across all simulations. This assumption is confirmed comparing the results presented at Figs. 2 and 4.

The effect of cooperation, as an effective strategy to increase the bundle delivery probability is even more pronounced in this routing protocol. Figure 4 shows that when a fully cooperative scenario is considered the bundle delivery probability increases approximately 2 %, 2 %, 3 %, 2 %, 2 %, 2 %, 2 %, and 1 % (for node cooperation percentage equal to 10, 20, 30, 40, 50, 60, 70, 80, and 90%) comparatively to an environment where 75 % of mobile nodes are able to cooperate. When compared to an environment with 50 % of cooperative mobile nodes, the fully cooperative approach present gains of approximately 7 %, 10 %, 14 %, 14 %, 15 %, 14 %, 14 %, 14 %, and 13 % respectively. Finally, when compared to the environment with 25 % of cooperative mobile nodes, the fully cooperative approach present gains of approximately 9 %, 14 %, 19 %, 20 %, 20 %, 20 %, 20 %, 20 %,

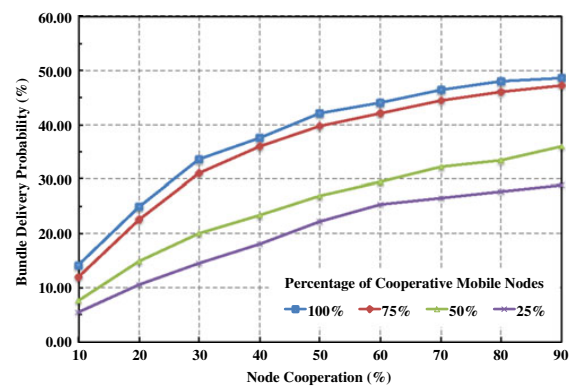


Fig. 4 Bundle delivery probability for Epidemic routing protocol as function of the cooperation percentage for 25, 50, 75, and 100 % of cooperative mobile nodes

20 %, and 20 % respectively for the same performance metric. The analysis of Fig. 4 allows concluding that increasing the percentage of cooperative mobile nodes above 75 %, does not improve significantly the bundle delivered probability for this simulation scenario.

Contrary to the observed results for First Contact routing protocol (Fig. 3), with the increase of nodes cooperation percentage, the fully cooperative scenario on Epidemic presents the lower results in terms of bundle average delivery delay (Fig. 5). However, it also presents a significantly decrease when compared to the scenario where only 25 % of mobile nodes are able to cooperate. In this scenario bundles arrive to its final destination 12, 19, 31, 41, 42, 53, 52, 55, and 59 min later (for node cooperation percentage equal to 10, 20, 30, 40, 50, 60, 70, 80, and 90%) when compared to the fully cooperative scenario. For other scenarios the fully cooperative only start to present a significantly decrease when nodes cooperate with 60 % or above of their resources. In the case where 75 % of nodes are able to cooperate, the fully cooperative scenario delivers bundles approximately 13, 12, 13, and 12 s sooner. This behavior was expected since similar delivery probabilities were observed.

4.4 Impact of cooperation for spray and wait routing protocol

Spray and Wait routing protocol is also considered a flooding-based routing protocol. However, contrary to Epidemic it limits the number of copies of each bundle in the network. In studies that consider this protocol, the binary version assumes the use of a limit number of copies equals to 4 ($N=4$). With this approach, binary version of Spray and Wait reduces some overhead of the pure epidemic diffusion. Consequently, it is expected that binary version of Spray and Wait present higher results in terms of bundle delivery probability and bundle average delivery delay. This observation is confirmed comparing Figs. 4 and 6.

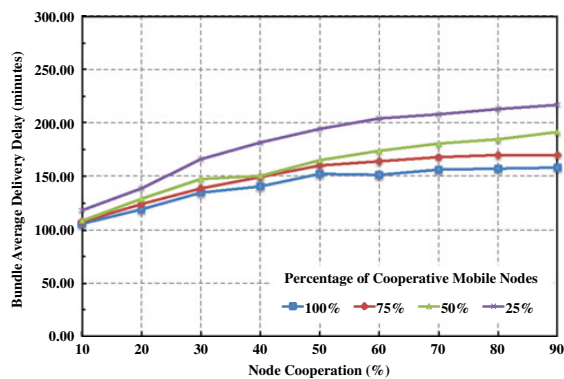


Fig. 5 Bundle average delivery delay for Epidemic routing protocol as function of the cooperation percentage for 25, 50, 75, and 100 % of cooperative mobile nodes

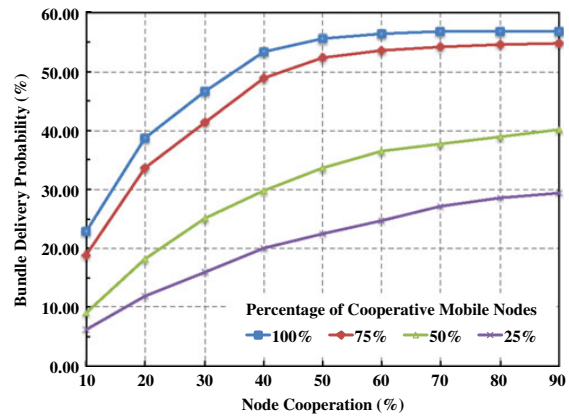


Fig. 6 Bundle delivery probability for binary version of Spray and Wait routing protocol as function of the cooperation percentage for 25, 50, 75, and 100 % of cooperative mobile nodes

The effect of node cooperation in the fully cooperative scenario presents the best results for simulations with the considered routing protocol. It presents gains of approximately 4 %, 5 %, 5 %, 4 %, 3 %, 3 %, 3 %, 2 %, and 2 % (for node cooperation percentage equal to 10, 20, 30, 40, 50, 60, 70, 80, and 90%) when compared to a scenario where only 75 % of mobile nodes are able to cooperate. When compared to the less cooperative scenario (25 % of cooperative mobile nodes) it present gains of approximately 17 %, 27 %, 31 %, 33 %, 33 %, 32 %, 30 %, 28 % and 27 % respectively. The analysis of Fig. 6 also allows to concluding that cooperation in flooding-based routing protocols that limits the number of copies per bundle increases significantly the bundle deliver probability.

The binary version of Spray and Wait not only registers one of the higher delivery probabilities, but also performs better in terms of bundle average delivery delay. Moreover, as can be observed in Fig. 7 as node cooperation percentage increases

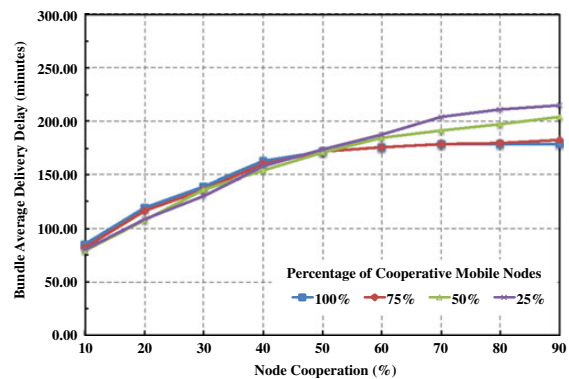


Fig. 7 Bundle average delivery delay for binary version of Spray and Wait routing protocol as function of the cooperation percentage for 25, 50, 75, and 100 % of cooperative mobile nodes

the bundle average delivery delay also increases. This performance metric presents similar results for all considered scenarios (25, 50, 75, and 100 % of cooperative nodes). However above 70 % of node resource cooperation, the fully cooperative scenario deliver bundles approximately 25, 32, and 37 min (for node cooperation percentage equal to 70, 80, and 90%) sooner than the scenario where only 25 % of nodes cooperate. When the scenario with 50 % of cooperative mobile nodes is considered, the fully cooperative scenario outperforms it by deliver bundles 13, 19, and 26 min sooner.

4.5 Impact of cooperation for PRoPHET routing protocol

PRoPHET is a probabilistic routing protocol that considers the history of node encounters and transitivity information to calculate probabilistic metric called delivery predictability. This metric is used to decide whether or not to forward a bundle at a contact opportunity. A bundle is forwarded to another node if the delivery predictability of the receptor node is higher than the sender node. Taking into account the recommendations presented [48] and the case study performed in [49], the value of β (transitive property) is 0.25.

As the above-presented results, increasing cooperation between network nodes, it contributes to an increase of the bundle delivery probability. In the specific case of PRoPHET by increasing cooperation between nodes will increase nodes delivery predictability, which leads to an improvement of the overall network performance. As may be seen in Fig. 8, the fully cooperative approach presents the best results in the bundle delivery probability metric. When compared to the 75 % of cooperative mobile nodes, results are very similar. However the fully cooperative scenario present gains of 1 %, 1 %, 2 %, 2 %, 2 %, 3 %, 3 %, and 3 % (for node cooperation percentage equal to 10, 20, 30, 40, 50, 60, 70, 80, and 90%). When compared to the other two cooperative scenarios, the fully cooperative scenario presents significant

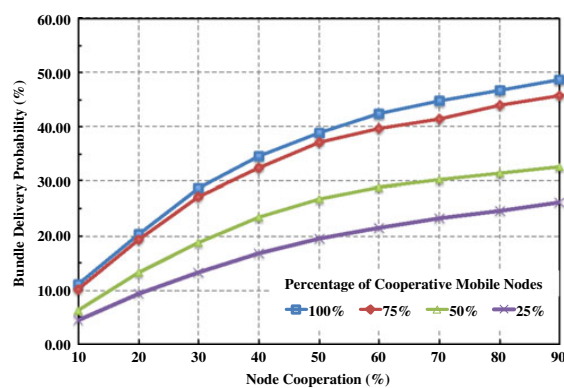


Fig. 8 Bundle delivery probability for PRoPHET routing protocol as function of the cooperation percentage for 25, 50, 75, and 100 % of cooperative mobile nodes

gains. Comparatively to the 50 % scenario it present gains of approximately 5 %, 7 %, 10 %, 11 %, 12 %, 14 %, 14 % 15 %, and 16 % respectively. When compared to the 25 % scenario, the fully cooperative scenario presents gains of approximately 7 %, 11 %, 16 %, 18 %, 19 %, 21 %, 22 %, 22 %, and 23 % respectively. These results confirm the importance of mobile nodes to cooperate between them in order to increase the bundle delivery probability.

From the analysis of Fig. 9, the behavior of bundle average delivery delay can be observed. As may be seen, the results of this metric are within the expected. By increasing the number of cooperative mobile nodes and the cooperation level of each mobile node the bundle average delivery delay increases. For all the considered scenarios the impact of node cooperation in this metric is even more evident when nodes cooperate with 20 % or above of their resources. Nevertheless, the fully cooperative scenario presents the best results. When compared to the 75 % of cooperative mobile nodes scenario, bundles arrive to its final destination 5, 6, 7, 9, 6, 6, 9, and 9 min (for node cooperation percentage equal to 20, 30, 40, 50, 60, 70, 80, and 90%) sooner. Comparably with the 50 % scenario, bundles arrive 9, 14, 18, 21, 19, 18, 17, and 16 min sooner. Finally when compared to the 25 % scenario, bundles arrive 15, 23, 27, 33, 30, 32, 33, and 34 min sooner.

4.6 Impact of cooperation for GeoSpray routing protocol

GeoSpray is a multiple-copy geographic routing protocol designed specially for VDTNs. This protocol exploits the mobility of vehicles and the location information provided by position devices (e.g., Global Positioning System), to support routing decision-making process. GeoSpray was designed to perform into sparse scenarios where communication opportunities are sporadic. GeoSpray also follows a hybrid approach inspired on GeOpps [50] and the binary version of Spray and Wait.

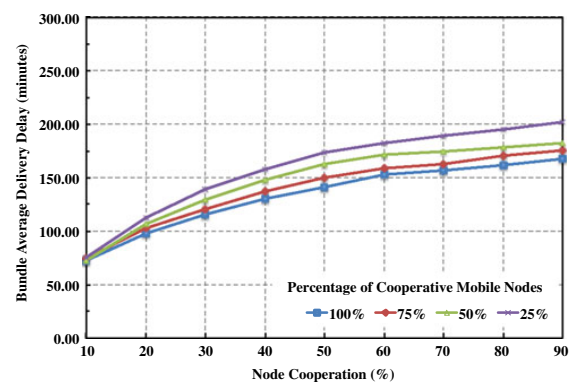


Fig. 9 Bundle average delivery delay for PRoPHET routing protocol as function of the cooperation percentage for 25, 50, 75, and 100 % of cooperative mobile nodes

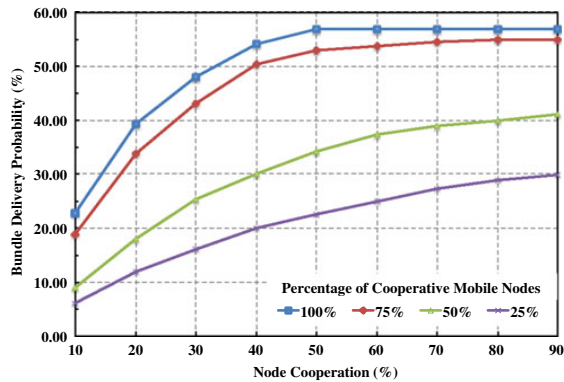


Fig. 10 Bundle delivery probability for GeoSpray routing protocol as function of the cooperation percentage for 25, 50, 75, and 100 % of cooperative mobile nodes

As may be seen in Fig. 10, the bundle delivery probability of this routing protocol is also affected by cooperation between network nodes. As the number of cooperative nodes increases the bundle delivery probability also increases. The percentage of cooperation that each node offers also affects this metric. As expected the fully cooperative approach presents the best results when compared to other considered scenarios. Comparably to the 75 % scenario, it present gains of approximately 4 %, 5 %, 5 %, 4 %, 4 %, 3 %, 2 %, 2 %, and 2 % (for node cooperation percentage equal to 20, 30, 40, 50, 60, 70, 80, and 90%). When compared to the 50 % of cooperative mobile nodes scenario, it presents gains of approximately 14 %, 21 %, 23 %, 24 %, 23 %, 19 %, 18 %, 17 %, and 16 % respectively. Finally, when compared to the 25 % of cooperative mobile nodes scenario, it present gains of approximately 17 %, 27 %, 32 %, 34 %, 34 %, 32 %, 29 %, 28 %, and 27 % respectively.

GeoSpray registers the higher delivery probabilities, but in terms of bundle average delivery delay the results are very similar to the binary version of Spray and Wait. Moreover, as

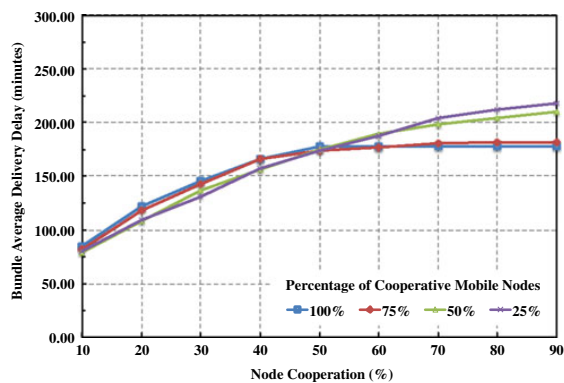


Fig. 11 Bundle average delivery delay for GeoSpray routing protocol as function of the cooperation percentage for 25, 50, 75, and 100 % of cooperative mobile nodes

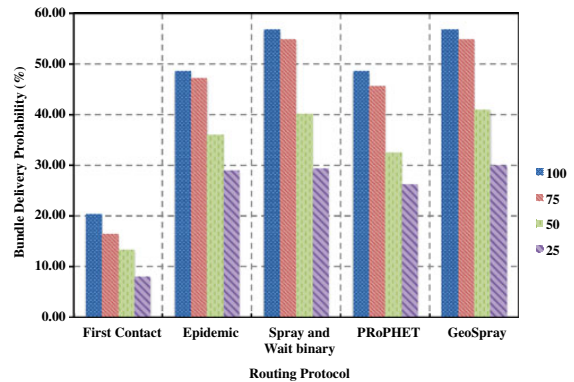


Fig. 12 Bundle delivery probability as function of the percentage of cooperative mobile nodes for First Contact, Epidemic, binary version of Spray and Wait, PRoPHET, and GeoSpray

can be observed in Fig. 11, as the node cooperation percentage increases the bundle average delivery delay also increases. This performance metric presents similar result for all considered scenarios (25, 50, 75, and 100 % of cooperative nodes). However, above 70 % of node resource cooperation, the fully cooperative scenario deliver bundles approximately 26, 34, and 40 min sooner (for node cooperation percentage equal to 70, 80, and 90%) than the scenario where only 25 % of nodes cooperate. Compared to the 50 % scenario bundles arrive to its final destination 20, 26, and 32 min sooner.

4.7 Discussion

This subsection overviews and discusses the results observed for all the conducted studies, considering different routing strategies. Figure 12 presents the bundle delivery probability for each considered routing protocol, assuming scenarios with different percentage of node cooperation. This figure emphasizes the results for the case when nodes share 90 % of their own

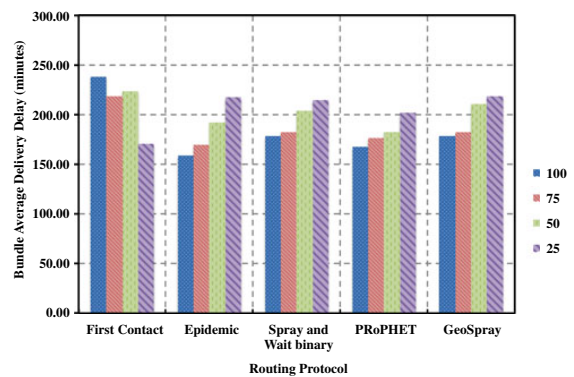


Fig. 13 Bundle average delivery delay as function of the percentage of cooperative mobile nodes for First Contact, Epidemic, binary version of Spray and Wait, PRoPHET, and GeoSpray

resources, since it was shown in previous subsections that this approach presents the best results in this metric. As may be seen in this Fig. 12, when the percentage of cooperative mobile nodes increases the bundle delivered probability also increases for all the considered routing protocols. As may be seen in this figure, one can conclude that GeoSpray performs better than the other protocols. Its performance is very similar to the binary version of Spray and Wait for all the considered scenarios. However, when scenarios with lower percentage of cooperative nodes are considered, GeoSpray presents a significant gain due to its better performance in scenarios with low density of mobile nodes. When compared to Epidemic, GeoSpray presents gains of 1 %, 2 %, 8 %, and 8 % (for scenarios with a percentage of cooperative nodes equal to 25, 50, 75, and 100). Assuming a probabilistic routing protocol, such as PRoPHET, the network performance continues to be worst when compared to GeoSpray. PRoPHET delivered less 4 %, 8 %, 9 %, and 8 % (for scenarios with a percentage of cooperative nodes equal to 25, 50, 75, and 100). The routing protocol with the worst behavior in this metric is First Contact. As expected it presents the lower percentage of delivery bundles, and when compared to GeoSpray, it delivers less 22 %, 28 %, 38 %, and 37 % of bundles (for scenarios with a percentage of cooperative nodes equal to 25, 50, 75, and 100).

In respect to the bundle average delivery delay that is shown in Fig. 13 only First Contact routing protocol diverges from the behavior shown by all the remaining routing protocols. As the percentage of cooperative nodes increases the bundle average delivery delay tends to increase. This is due to the unique characteristics of First Contact. Contrary to flooding-based approaches, First Contact only keeps at most one copy of each bundle in the entire network. By increasing the number of possible receptors leads to bundles traveling a longer path until they reach their final destination.

5 Conclusions and future work

Vehicular Delay-Tolerant Networks (VDTNs) try to enable communications in scenarios characterized by network partition and disruption. In addition, these networks experience unconventional difficulties on data communications due to sparse connectivity, network partitioning, and even no end-to-end connectivity. To overcome these issues, VDTNs rely on cooperation between nodes to increase bundles delivered across the network. Nodes that are unwilling to cooperate tend to affect significantly the network operation and performance.

This paper addressed the research problem of node cooperation in the VDTN architecture. The related literature about this topic was surveyed and discussed. In addition, several studies were conducted to evaluate the impact of cooperation on the performance of VDTNs using five routing protocols, each one with single characteristics (First Contact, Epidemic,

Spray and Wait, PRoPHET, and GeoSpray). It was shown that GeoSpray protocol performs better than the rest of the studied routing protocols. It was also concluded that cooperation between nodes improves the overall bundle delivery probability, leading to a better performance of VDTN networks.

Further research studies may be conducted taking into account the deep understanding about the implications of node cooperation over VDTNs networks presented by this paper. A reputation system for cooperative VDTNs will be proposed and studied. This paper may also contribute to the creation of new cooperation approaches for VDTNs.

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Chapter 4

Performance evaluation of cooperative strategies for Vehicular Delay-Tolerant Networks

This chapter is based on the following paper:

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João A. F. F. Dias, Joel J.P C. Rodrigues, and Liang Zhou

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SPECIAL ISSUE PAPER

Performance evaluation of cooperative strategies for Vehicular Delay-Tolerant Networks

João A. F. F. Dias¹, Joel J. P. C. Rodrigues^{1*} and Liang Zhou²¹ Instituto de Telecomunicações, University of Beira Interior, Covilhã, Portugal² Nanjing University of Posts and Telecommunications, China

ABSTRACT

Vehicular Delay-Tolerant Networks emerge as a vehicular networks technology that can be deployed on a wide range of scenarios. For example, it can be applied in sparse and remote regions characterised by sparse connectivity to allow data communications, as well as in urban scenarios. Frequent network partitioning, intermittent connectivity, long propagation delays, high error rates and short contact durations characterise these environments. To overcome some of these issues, cooperation approaches should be considered to force nodes to share their own resources. It is important to perform this task because nodes may be unwilling to cooperate due to a selfish behaviour. Selfish nodes affect considerably the functionality and the performance of the overall network. This paper overviews the most relevant contributions on cooperation for vehicular networks. It also proposes four different cooperation strategies for Vehicular Delay-Tolerant Networks and studies their impact on the performance of the network. These strategies are enforced on two delay-tolerant networks routing protocols (Epidemic and Spray-and-Wait). Across all the experiments, it was shown that all the strategies contribute to the improvement of the overall network performance by increasing the bundle delivery probability and consequently decrease the bundle average delivery delay. Copyright © 2013 John Wiley & Sons, Ltd.

*Correspondence

Joel J. P. C. Rodrigues, Instituto de Telecomunicações, University of Beira interior, Rua Marquês D'Ávila e Bolama, 6201-001 Covilhã, Portugal.

E-mail: joelj@ieee.org

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1. INTRODUCTION

Vehicular Delay-Tolerant Networks (VDTNs)[1] were proposed as a solution to overcome some of the numerous issues faced on vehicular networks. Most of these issues arise as a direct consequence of vehicles behaviour (e.g. speed and mobility). For example, because of its high mobility, the network topology changes constantly, leading to intermittent connectivity and, consequently, to significant loss rates [2–5].

Vehicular Delay-Tolerant Networks collect important contributions from other vehicular network architectures such as Vehicular Ad Hoc Networks (VANETs) [2–7] and Delay-Tolerant Networks (DTNs) applied to vehicular networks environments [8]. For example, the communication architecture from VANETs was considered. In VDTNs, vehicles may communicate directly with other vehicles, establishing a vehicle-to-vehicle communication, or with roadside infrastructures performing a vehicle-to-infrastructure communication. A hybrid architecture combining the best of both approaches may also be considered. VDTNs deploy the well-known store-carry-

and-forward paradigm proposed for DTNs. By using this paradigm, vehicles move along roads expecting to find other vehicles or roadside infrastructures to communicate. Vehicles store data while a contact opportunity is not available. When a contact opportunity is available, data are forwarded using a specific routing protocol. This process is repeated until data reach their final destination.

Contrary to DTNs used in vehicular environments, VDTN-layered architecture deploys the two lower layers of open systems interconnection model, because the VDTN layer supports physical layer services and protocols, and connection management services related to the data link layer. The intermittent connectivity and the discrete nature of transfer opportunities in the transportation system of the VDTNs scenarios motivate the routing of large size messages instead of small size IP packets, addressing the network complexity at the edge of the network and keep simple its core. This results in fewer packets processing and routing decisions, which can be translated to less complexity, lower cost and energy savings, which will improve the overall network performance when

compared with the DTN architecture. To allow VDTNs having an efficient behaviour in terms of energy consumption and networks operation for bundle scheduling and exchange, the core network considers two different planes (control and data planes). It performs out-of-band signalling following, for instance, the optical burst switching approach [9]. At the control plane, two consecutive nodes exchange control information in order to schedule, reserve resources and optimise the data exchange performed by the data plane. For example, they can exchange information related to contact time and duration, storage capacity and power constraints, speed, location or even supported link technology. On the basis of this information, communication is set up, and resources are reserved for the data plane. At the data plane, data are exchanged at the scheduled time, and buffer maintenance is performed as well as other network functionalities (e.g. traffic classification and data aggregation/de-aggregation at the edge of the networks).

Vehicular Delay-Tolerant Networks consider three types of nodes: terminal, relay and mobile nodes. Terminal nodes (either fixed or mobile) are placed at the edge of the network and are responsible for the bundle aggregation and de-aggregation. Relay nodes are fixed devices placed at crossroads with storage capabilities to increase the number of contacts between network nodes. The increase of contact opportunities leads to an improvement of the overall network performance by increasing the number of delivered bundles and decreasing the average delivery delay [10]. In this type of nodes, bundles are stored until a promising contact opportunity is available to be carried closing to their final destination. Finally, mobile nodes (vehicles) travel along roads and interact with all VDTN node types. Mobile nodes can also be used as terminal nodes.

Several studies have been conducted to improve the performance of VDTN networks. However, there are still several open issues that should be overcome. One of these open issues is cooperation between network nodes. Enforcing cooperation in VDTNs is not easy; then, several technical challenges must be overcome. For example, it is important to study the best way to stimulate nodes to cooperate to create optimal cooperative systems that provide quality of service to increase the network performance without compromising or deteriorating nodes data. It is also important to afford nodes with sophisticated schedulers. To deploy both of the previously presented cooperation approaches, it should be considered that two types of cooperative nodes with different behaviour may be found. One of them may be characterised by a selfish behaviour, which means that this type of nodes is unwilling to share its own resources. Contrary to selfish nodes, cooperative nodes share their own resources to help others, but their performance may be affected by selfish nodes.

It is important to stimulate all the nodes to cooperate, so this paper studies the impact of four cooperative schemes proposed for VDTNs. These schemes consider different ways to stimulate nodes to share their own resources. For

example, nodes may be forced to cooperate a fixed or a random percentage of their own resources. Other approaches consider the node performance to select the percentage of resource sharing. Then, the main contributions of this paper are the following:

- A review of the state of the art, considering the most relevant contributions on network cooperation for vehicular networks
- Proposal of four cooperation strategies for VDTNs
- Exhaustive studies to evaluate the network performance improvement considering the proposed cooperation strategies on VDTN nodes, using the most relevant routing protocols

The remainder of this paper is organised as follows. Section 2 focuses on the cooperation problem and presents a detailed review of the state of the art on cooperation in vehicular networks. Section 3 describes the proposed cooperation strategies and how they may be enforced in VDTNs, whereas Section 3.1 presents the experimental settings, and the performance assessment of cooperation strategies in VDTNs is analysed in Section 3.2. Section 5 concludes the paper providing a final summary of the study and suggesting further research works.

2. RELATED WORK

Vehicular communications may be deployed at multiple scenarios considering different regions with completely different goals. For example, they can be used in rural scenarios to enable communications between sparse regions. Emergency vehicles can also be used when all communications are broken because of a catastrophic event. Independent of the scenario where vehicular networks are deployed, it is important to keep in mind that a good routing protocol is not enough to ensure an optimal network performance. This is important because, in such networks, nodes may have two types of behaviour: selfish and cooperative. Selfish nodes may belong to individual users that are not interested to share their own resources to forward messages from other users. For these nodes, sharing resources without receiving anything for this cooperation is not appealing. Cooperative nodes are nodes that travel along roads, which increases the probability to find and communicate with other nodes. This type of nodes is usually chosen as message forwarders. But being picked as a message forwarder may force nodes to diverge from the protocol to save its own data and resources. To create a solution that brings the best of these two types of nodes, it is very important to offer them incentives as a reward of their cooperative behaviour.

Different approaches of cooperation are proposed in the literature. For example, in mobile ad hoc networks [11–13], there are two types of incentives for a cooperative behaviour. The first one uses the node reputation to decide if a node is well behaved and suitable to communicate. If a node has a bad reputation, it will be marked as a

noncooperative node. This will make other nodes ignore communication requests sent by this node. This type of incentives is usually included in reputation-based approaches [14–18]. On the other hand, credit-based approaches are used when nodes collect credits as a reward of its cooperative behaviour [19, 20]. These two types of incentives are also considered in vehicular networks.

Regarding VANETs, different schemes and systems were proposed to improve network performance by enabling cooperation among nodes. For example, in [21], authors present a scheme where nodes are rewarded each time they cooperate with another one. This scheme takes into consideration storage constraints to calculate cooperation levels of each node. By doing this, the best interests of each node are preserved.

Wang *et al.* [22] propose a scheme that is used to detect selfish nodes. By using a dynamic trust token, selfish nodes are marked as uncooperative nodes to notify other nodes of its behaviour. To do that, data packets are forwarded with an attached token to evaluate its correctness. To accept a packet, nodes evaluate this token to prove their sender.

In [23], a scheme to stimulate cooperation in VANETs is proposed. This scheme rewards all nodes that participate in the forwarding process of a specific message. Each time a message reaches its destination, an advice is sent to all the network nodes. When a node receives this advice, it should report the source node about its participation in the forwarding process. This behaviour allows source node to calculate the final contribution of each node in the forwarding process. The final contribution is calculated through the sum of the partial contribution given by each node in the forwarding tree. Each intermediate node will receive a percentage as a reward for a message forwarding.

By definition, the store-carry-and-forward paradigm from DTNs assumes node cooperation. This allows nodes to store and forward bundles, not only in their own interest but also in the interest of other nodes. Considering this, C-ARQ [24] and DC-ARQ [25] are proposed to stimulate cooperation between DTN nodes. C-ARQ tries to reduce packet losses during transmissions between vehicles and fixed access points. It allows communications between vehicles where an access point is not available. DC-ARQ is a variant of the scheme proposed in [24] but differs from it because it only maintains an active cooperation while nodes are in range of the access point.

In [26], authors present a theoretical model to calculate the average cooperation delay of the persistent relay carrier sensing multiple access. These theoretical models try to overcome some of the limitations presented in [27]. To overcome them, authors consider that relay nodes do not need a dedicated backoff counter for cooperation phases, and this counter is reset each time a new cooperation phase is initiated.

Resta *et al.* [28] present a study about the impact of different levels of cooperation in three well-known routing protocols (Epidemic [29], Two-Hop [30] and Spray-and-Wait [31]). This study considers a game theory scheme

to stimulate nodes to cooperate. It also includes balanced policies allowing comparisons between cooperative and uncooperative scenarios. It was shown that cooperative scenario presents the best results for all the considered routing protocols.

In [32], nodes with an irregular performance are detected and excluded from the network tree. A node with an irregular behaviour is a node that tries to send more of its own data and less peer data, than a well-behaved node. They may also act as false cooperative nodes by accepting all the incoming messages to drop them immediately. Studies confirm that detecting these misbehaving nodes is very important because such nodes have a huge impact on the performance of well-behaved nodes.

Following DTNs, VDTNs also start to address the cooperation problem. In [33], the impact of cooperation is studied when an urban scenario is considered. In this study, cooperation was divided into two different approaches. In the first one, cooperation is enforced at the control plane and tries to stimulate nodes to exchange signalling messages containing useful information about nodes. After, this information will be used to accept or deny a contact opportunity. The second one focuses on cooperation at data plane level and stimulates nodes to share their own resources in favour of other network nodes. Conducted studies show an improvement of the overall network performance when cooperation approaches are considered.

This section overviewed the most important contributions already proposed to deal with cooperation issues in vehicular networks. They may be considered as a starting point to propose new schemes for cooperation in VDTNs.

3. COOPERATION STRATEGIES FOR VEHICULAR DELAY-TOLERANT NETWORKS

Vehicular Delay-Tolerant Networks relay on cooperation between network nodes to achieve a good performance in a wide range of scenarios. During a contact opportunity, cooperation between nodes can be performed at two different levels, considering both control and data planes. At control plane level, nodes cooperate between them by exchanging relevant information (e.g. contact time and duration, node location, speed and storage capacity), which allows more accurately to predict the period of time that a contact is available for data exchange. At the data plane level, nodes may also cooperate by sharing their own resources (e.g. link bandwidth and storage capacity) with another one to maximise the usage of data link resources. In addition, cooperation at the data plane may also include sending bundles from others that are stored on nodes buffer.

In this paper, four different approaches for cooperation in VDTNs are proposed. Next subsections present and describe these four schemes, highlighting their most important characteristics.

3.1. Static Mandatory Cooperation and Random Mandatory Cooperation schemes

Static Mandatory Cooperation (SMC) and Random Mandatory Cooperation (RMC) schemes define two levels of cooperation: cooperative buffer threshold (α) and cooperative link threshold (β). At the cooperative buffer threshold level (BT), it is set the percentage of buffer space that will be reserved to store bundles from other nodes. The cooperative link threshold level (LT) sets the amount of time that a node spends to send messages from others. At the SMC, when a node is in contact with another one, it is forced to cooperate with a certain percentage of its own resources. For example, if the cooperation percentage is defined at 50%, this means that each node should share 50% of its own storage capacity to store bundles from others. In addition, nodes should spend 50% of the available contact time to send bundles from others. The behaviour of the RCM cooperative scheme is similar to the SMC differing from the previously presented scheme by randomly choosing the cooperation percentage. To generate the random cooperative percentage, a Gaussian distribution is considered. Equation (3.1) shows how buffer capacity and threshold are calculated, where *bufferSize* represents the node buffer size, in megabytes (MB). The link threshold is calculated according to Equation (3.2), where *bytesCanBeTransferred* is the maximum amount of bytes that can be transferred during the established contact opportunity. The random cooperative percentage is calculated according to Equation (3.3)

$$BT = \begin{cases} \alpha * BufferSize \\ (1-\alpha) * BufferSize \end{cases}, \alpha = BufferThreshold \quad (3.1)$$

$$LT = \begin{cases} \beta * bytesCanBeTransferred \\ (1-\beta) * bytesCanBeTransferred \end{cases}, \beta = LinkThreshold \quad (3.2)$$

$$RMC_{\alpha} = x * \sqrt{-2 * \frac{\log(r)}{r}} \quad (3.3)$$

3.2. Node Performance Cooperation (NPC) and Inverse Node Performance Cooperation (INPC) schemes

Node Performance Cooperation (NPC) and Inverse Node Performance Cooperation (INPC) schemes take into account the nodes performance to choose the percentage of resources to share. To calculate a node performance using the NPC scheme, the ratio between the number of sent and received messages is considered. As the main goal of any network is to deliver the largest possible number of messages, a node that sends more bundles than those who receive has a higher cooperation ratio and will be marked as a well-behaved node. This type of nodes will share higher percentage of their own resources. Furthermore, nodes that send less bundles than received have a lower cooperation ratio and will be encouraged

to cooperate with a higher percentage. This is achieved by forcing this type of nodes to spend more time sending messages and less receiving them. The INPC scheme uses the same approach of the NPC but differs from it being considered the inverse ratio between the number of sent and received messages. This will allow nodes with selfish behaviour to cooperate more. Equations (3.4) and (3.5) show how cooperation percentage is calculated for both schemes.

$$NPC_{CRatio} = \frac{SentMessages}{ReceiveMessages} \quad (3.4)$$

$$INPC_{CRatio} = 1 - \frac{SentMessages}{RecieveMessages} \quad (3.5)$$

4. EXPERIMENTAL SETTINGS

The performance analysis of the previously presented cooperation schemes was conducted using the VDTNsim simulator [34]. Performance experiments were performed considering a real map of Serra da Estrela region, Portugal (shown in Figure 1). In this scenario, 25 terminal nodes are placed at real-world sparse villages with a buffer capacity of 250 MB. Each terminal node acts as a traffic source and traffic link and generates bundles with a creation interval in the range of [15, 30] min. In this study, bundle time-to-live is not considered, so bundles are dropped only in case of buffer congestion. To increase the number of contact opportunities, six relay nodes were placed at the most important crossroads with a buffer capacity of 500 MB. To

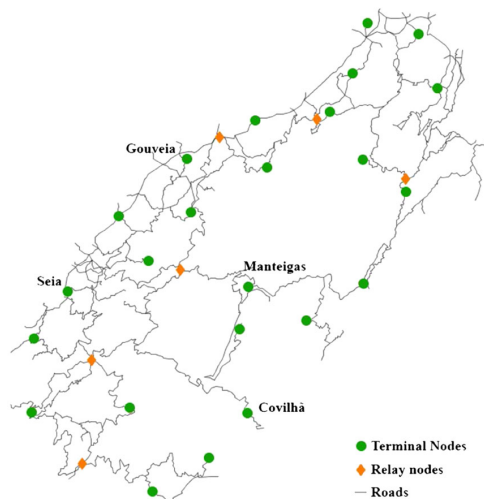


Figure 1. Illustration of the Serra da Estrela region (Portugal) with the location of terminal and relay nodes.

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transport bundles between terminal nodes, mobile nodes move along roads with a velocity in range of [30, 80] km/h and have a buffer capacity of 125 MB. When a mobile node reaches a terminal node, it randomly waits between 15 to 30 min. Thus, a new random terminal node is chosen to be the next destination point. To study the impact of the previously presented studies, the number of cooperative mobile nodes changes in the range of [5, 30]. All the network nodes are equipped with the standard IEEE 802.11b interface to allow communications with other nodes and a data rate of 6 Mbps [35]. IEEE 802.11b were chosen to allow the integration of these cooperative schemes in the VDTN@Lab testbed [36].

For all the experiments, the creation and exchanging of bundles is simulated for a period of time of 12 h. Four different scenarios with 5, 10, 15 and 30 mobile nodes are considered. For each scenario, the performance of Epidemic [37,38] and Binary Spray-and-Wait [31] is analysed. Epidemic is a flooding-based routing protocol that replicates bundles at each contact opportunity. With this routing protocol, a node can forward as many replicas as it has requested to send. On the other hand, Spray-and-Wait limits the number of copies of each bundle. The performance of this routing protocol is divided into two phases: 'spray' and 'wait'. In the 'spray phase', for each original bundle, R copies of each bundle are forwarded to R distinct relays. At the 'wait phase', this routing protocol waits until any of the R relays deliver the message to the destination node. In this work, the binary version of Spray-and-Wait is considered, where the source node starts with a number of N copies (in this study, four copies were considered) to be forwarded per bundle. Then, at a given node A that has more than one bundle copies, forwards to other node $N/2$ bundle copies, keeping the rest of the copies for it. When a node transports only one copy left, it only forwards this copy to the final destination.

The bundle delivery probability and the bundle average delivery delay are the performance metrics considered in all the conducted studies. The bundle delivery probability (D_P) is defined as the ratio between the number of unique bundles (i.e. does not count bundle replicas) that have reached the final destination node(s) and the total number of unique bundles that was created at the source node(s). It is calculated according to Equation (4.1), where D_P is the bundle delivery probability, D_B is the total number of unique delivered bundles and C_B is the total number of unique created bundles.

The bundle average delivery delay is defined as the average time between bundles creation and delivery. It is calculated according to Equation (4.2), where D_D is the bundle average delivery delay, Td_i is the time when the bundle i was delivered, Tc_i is the time when the bundle i was created and D_B is the total number of unique delivered bundles.

$$D_P = \frac{D_B}{C_B} \quad (4.1)$$

$$D_D = \frac{\sum_{i=1}^{D_B} (Td_i - Tc_i)}{D_B} \quad (4.2)$$

5. PERFORMANCE ANALYSIS

This section focuses on the performance analysis of the results obtained for the experiments conducted with the previously described scenario. Figure 2 shows the results observed for the bundle delivery probability when the four previously presented cooperation approaches are enforced on the Epidemic routing protocol. It can be observed that SMC scheme performs better than the other schemes. Comparing with the RMC scheme, it improves the overall network performance approximately about 22%, 39%, 40% and 44% (for number of cooperative vehicles equals to 5, 10, 15 and 30, respectively). These results are not only due to the Epidemic's pure flooding behaviour that results on network resources wasting but also to the way cooperation is enforced in network nodes. These results show that forcing nodes to cooperate with a constant percentage leads to a better network performance because nodes do not diverge from the protocol. When compared with NPC, the SMC scheme presents gains of approximately 3%, 18%, 18% and 24%. Finally, SMC improves the bundle delivery probability approximately about 15%, 30%, 21% and 27% when compared with INPC approach. These two last schemes perform better than the RMC because when nodes diverge from the protocol, both methods implement measures to make them return to the protocol.

As may also be seen in Figure 2, as the number of cooperative mobile nodes increases, the bundle delivery probability also increases. This is due to the higher number of contact opportunities that occur during the simulation period, which allow nodes to send a higher number

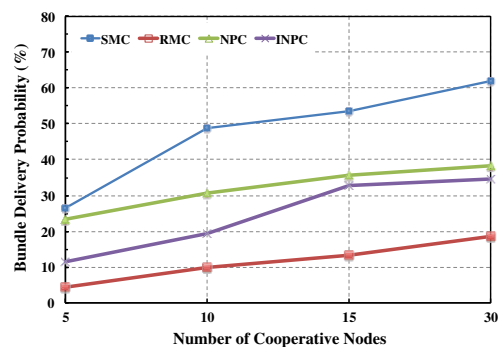


Figure 2. Bundle delivery probability as function of the number of cooperative nodes for Static Mandatory Cooperation, Random Mandatory Cooperation, Node Performance Cooperation and Inverse Node Performance Cooperation cooperation strategies with Epidemic routing protocol.

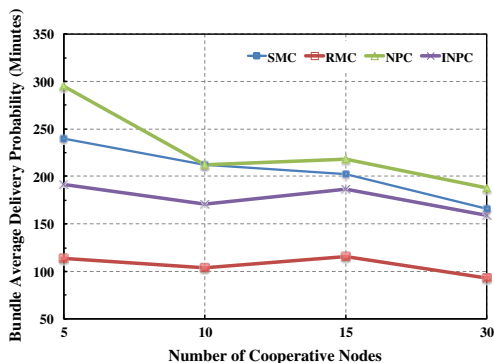


Figure 3. Bundle average delivery probability as function of the number of cooperative nodes for Static Mandatory Cooperation, Random Mandatory Cooperation, Node Performance Cooperation and Inverse Node Performance Cooperation strategies with Epidemic routing protocol.

of bundles. As a consequence of the contact opportunities increasing, the bundle average delivery delay tends to decrease, as may be seen in Figure 3.

Spray-and-Wait limits the total number of replicas per bundle, which leads to less network transmissions. By doing this, it reduces some of the overhead of the pure epidemic diffusion. As may be seen in Figures 4 and 5, Spray-and-Wait performs better than Epidemic, presenting higher delivery ratios across all simulations, in this resource constrained network scenario.

The effect of the proposed cooperative approaches, as a strategy to increase the overall network performance, is even more pronounced in this routing protocol. Figure 4 shows that when nodes follow the SMC scheme, the bundle delivery probability increases when compared with other schemes. When compared with the RMC scheme, it increases approximately 23%, 39%, 41% and 38% (for number of cooperative mobile nodes equals to 5, 10, 15 and 30, respectively). Due to the Spray-and-Wait routing behaviour, the NPC scheme performs much better than in Epidemic. Reducing the number of copies per bundle in the network allows nodes to store more unique bundles from others. Consequently, this allows nodes to send more bundles because they have on their buffers a higher number of distinct bundles. However, it performs worst than the SMC, by delivering less 4%, 5%, 6% and 3% (for number of cooperative mobile nodes equals to 5, 10, 15 and 30, respectively). Finally, the INPC delivers less 21%, 35%, 17% and 18%, respectively, when compared with the SMC scheme.

In terms of bundle average delivery delay, the performance of Spray-and-Wait is similar to Epidemic. SMC and NPC schemes deliver bundles later and present a similar performance. However, SMC delivers bundles approximately 3, 2, 7 and 2 min sooner (for number of cooperative mobile nodes equals to 5, 10, 15 and 30). Figure 5 also

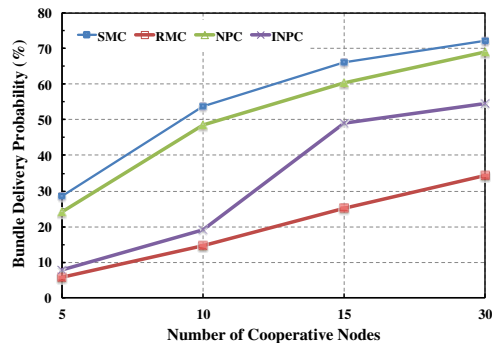


Figure 4. Effect of cooperative approaches on the bundle delivery probability as function of the number of cooperative nodes for Static Mandatory Cooperation, Random Mandatory Cooperation, Node Performance Cooperation and Inverse Node Performance Cooperation strategies with Spray-and-Wait routing protocol.

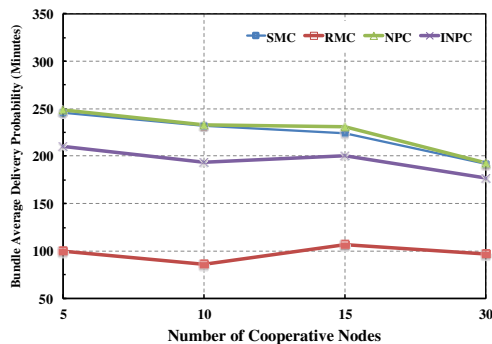


Figure 5. Effect of cooperative approaches on the bundle average delivery probability as function of the number of cooperative nodes for Static Mandatory Cooperation, Random Mandatory Cooperation, Node Performance Cooperation and Inverse Node Performance Cooperation strategies with Spray-and-Wait routing protocol.

shows that bundle average delay tends to decrease as the number of cooperative mobile nodes increases.

6. CONCLUSION AND FUTURE WORK

Vehicular Delay-Tolerant Networks are a recent topic that tries to overcome the most challenging issues of vehicular communications to deploy them in challenging environments such as rural and sparse regions. However, VDTNs still face unconventional difficulties on data communications due to sparse and intermittent connectivity, or even the absence of an end-to-end path between the source and

destination nodes. To deliver bundles, cooperation strategies must be considered to force nodes to exchange bundles during a contact opportunity.

This paper focused on the node cooperation problem and proposed four different schemes to be enforced in VDTNs. The related literature about the topic was surveyed. In addition, a performance study to evaluate the impact of the proposed strategies on the performance of VDTNs considering two DTN routing protocols (Epidemic and Spray-and-Wait). It was shown that the SMC strategy (that forces nodes to cooperate always with the same percentage) performs better than the rest of the proposed strategies. All the strategies present better results when enforced on the Spray-and-Wait routing protocol.

This work may be used as a base to develop new cooperative strategies, such as a cooperative system that rewards nodes that are willing to share their own resources to help other nodes. It may be suggested for further research works.

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Chapter 5

Performance evaluation of a cooperative reputation system for Vehicular Delay-Tolerant Networks

This chapter is based on the following paper:

Performance evaluation of a cooperative reputation system for Vehicular Delay-Tolerant Networks

João A. F. F. Dias, Joel J. P. C. Rodrigues, Lei Shu, and Sana Ullah

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RESEARCH

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Performance evaluation of a cooperative reputation system for vehicular delay-tolerant networks

João AFF Dias¹, Joel JPC Rodrigues^{1*}, Lei Shu² and Sana Ullah³**Abstract**

In the last decade, both scientific community and automotive industry enabled communications among vehicles in different kinds of scenarios proposing different vehicular architectures. Vehicular delay-tolerant networks (VDTNs) were proposed as a solution to overcome some of the issues found in other vehicular architectures, namely, in dispersed regions and emergency scenarios. Most of these issues arise from the unique characteristics of vehicular networks. Contrary to delay-tolerant networks (DTNs), VDTNs place the bundle layer under the network layer in order to simplify the layered architecture and enable communications in sparse regions characterized by long propagation delays, high error rates, and short contact durations. However, such characteristics turn contacts very important in order to exchange as much information as possible between nodes at every contact opportunity. One way to accomplish this goal is to enforce cooperation between network nodes. To promote cooperation among nodes, it is important that nodes share their own resources to deliver messages from others. This can be a very difficult task, if selfish nodes affect the performance of cooperative nodes. This paper studies the performance of a cooperative reputation system that detects, identify, and avoid communications with selfish nodes. Two scenarios were considered across all the experiments enforcing three different routing protocols (First Contact, Spray and Wait, and GeoSpray). For both scenarios, it was shown that reputation mechanisms that punish aggressively selfish nodes contribute to increase the overall network performance.

Keywords: Vehicular delay-tolerant networks; Cooperation; Reputation system; Selfish nodes; Simulation; Performance evaluation

1 Introduction

Vehicular networks have been emerging as a suitable solution to enable communications in different kind of scenarios using vehicles (i.e., cars, buses, trams, etc.). Several architectures, like vehicular *ad hoc* networks (VANETs) [1] and delay-tolerant networks (DTNs) [2], were proposed to solve several issues in such networks. Vehicular delay-tolerant networks (VDTNs) [3] appeared as a breakthrough DTN-based solution that tries to overcome several issues found in other vehicular architectures, such as long delays and sporadic connections. To support communications, VDTNs propose an architecture based on three design principles: (i) an Internet

Protocol (IP) over VDTN approach, (ii) an end-to-end, asynchronous, and variable-length bundle-oriented communication; (iii) a separation between control and data planes performing out-of-band-signaling.

VDTNs follow a store-carry-and-forward paradigm similar to the one that is implemented by DTNs. This approach allows VDTNs to solve several problems caused by intermittency, disconnection, and long delays. However, it distinguishes itself from DTNs by introducing the bundle layer under the network layer. This approach also assumes two logical planes (a control and a data plane). At the control plane, nodes exchange signaling messages in order to reserve resources (to be used at the data plane) and perform several routing decisions. At a given node, if there are bundles to exchange, the data plane is activated during the estimated contact duration time, and functions like queuing, scheduling, or

* Correspondence: joeljrc@ieee.org

¹Instituto de Telecomunicações, University of Beira Interior, Covilhã 6201-001, Portugal

Full list of author information is available at the end of the article



traffic classification are performed. Data bundles aggregation/de-aggregation is performed at the edge of the network. This approach is very important because it not only ensures the optimization of the available data plane resources (e.g., storage and bandwidth) but also allows power saving, which is very important for energy-constrained network nodes, such as stationary relay nodes [3,4].

VDTNs consider three types of nodes: terminal, relay, and mobile. Both fixed and mobile nodes can act as terminal nodes. Fixed nodes work as access points to the VDTN and may act as traffic source and traffic sinks. Stationary relay nodes, with store-and-forward capabilities, are placed at road intersections and interact with mobile nodes in order to improve the number of contact opportunities that contribute to increase the overall network performance [5]. Mobile nodes can be the source or destination of data, but usually they carry data among different nodes (both fixed and mobile). Although in the already conducted studies, VDTNs still present a large number of technical challenges that should be overcome. One of these open issues is cooperation between network nodes. Previous studies on this topic [6] show that enforcing cooperation in VDTNs is not an easy task. For example, it is important to stimulate nodes to cooperate in order to create an optimal cooperative system that provides quality of service (QoS) to increase the overall network performance without compromising or deteriorating data. One way to achieve this issue is to afford nodes with sophisticated schedulers. These schedulers should take into account that cooperative networks should assume two types of nodes: selfish and cooperative. Selfish nodes are unwilling to cooperate and in most cases they receive bundles forwarded by other nodes to drop them immediately. This behavior contributes to a huge waste of network resources (e.g., power). Contrary to selfish nodes, cooperative nodes share their own resources to store-and-forward bundles from others. However, the behavior of selfish nodes may affect their performance.

In order to reduce the impact of selfish nodes, an optimized reputation system for VDTNs that considers nodes reputation scores calculated through nodes performance is proposed. For example, each time nodes successfully deliver a bundle, their reputation increases. However, each time they drop a bundle without sending it at least once, their reputation decreases. This system considers four different ways to penalize nodes with a selfish behavior. All four approaches distinguish itself from others by the way they reward/penalize nodes by their behavior. Then, the main contributions of this paper are the following:

- A review of the state of the art, considering the most relevant contributions on cooperation and reputation systems for vehicular networks

- Proposal of an optimized version of the reputation system already proposed for VDTNs with four different strategies to identify and avoid selfish nodes
- Exhaustive studies to evaluate the network performance improvement considering the proposed reputation system on VDTN nodes, using two different scenarios and the most relevant routing protocols

The remainder of this paper is organized as follows. Section 2 focuses on the cooperation problem and presents a review of the state of the art on cooperation and reputation systems for vehicular networks. Section 3 describes the proposed optimized reputation system and how it can be enforced in VDTNs, whereas Section 4 presents the experimental settings considered on the performance studies. The performance assessment of the proposed reputation system in VDTNs considering an urban scenario is presented on Section 5, while Section 6 emphasizes the obtained results by the proposed reputation system when deployed on a rural environment. Finally, Section 7 concludes the paper providing a final summary of the study and suggests further research topics.

2 Related work

In challenging environments characterized by long delays and sporadic connections, it is very important to ensure that nodes cooperate with each other in order to carry messages from the source to destination. Ensuring cooperation between network nodes may be a tough task due to the misbehavior of network nodes. Nodes may diverge from the protocol to save their own data and resources. Then, nodes may also diverge from the protocol and be unwilling to cooperate due to a selfish behavior. Selfish nodes may belong to individual users (nodes) that are not interested to share their own resources to forward messages from other users (nodes). In both conditions, this selfish behavior severely affects the overall network performance [7].

A possible solution to minimize the effects of misbehavior nodes is to create sophisticated reputation systems that allow nodes to detect, identify, and avoid such nodes. Several approaches were already been proposed for VANETs. For example, CONFIDANT scheme [8,9] was proposed to incentive nodes to cooperate by detecting and isolating misbehavior nodes. To accomplish such task, this scheme implements a system composed by four components: a monitor, a trust manager, a path manager, and a reputation score. The monitor, in conjunction with the trust manager, detects any misbehavior node and uses the collected information to make routing decisions. Based in the routing decision made by the

monitor, the path manager calculates the optimal path avoiding misbehavior nodes. To calculate the optimal path, the reputation score of each node is considered. The CORE scheme, proposed in [10], considers the following three different kinds of mechanisms to select which node can use network services: (i) subjective, calculated based on direct observation, (ii) indirect reputation calculated according to information provided by other nodes, and (iii) functional reputation calculated using a specified function. In [11], authors propose a reputation system that encourages nodes to cooperate between them and punish misbehavior nodes. This system works under the principle that cooperation between nodes is performed by forwarding packets without any loss or network performance degradation. To avoid misbehavior nodes, this scheme detects and punishes nodes using a reputation management system (RMS) as an extension of the source routing protocol (SRP) [12].

Dotzer et al. [13] propose a reputation system for VANETs called VARS. This scheme assigns a reputation score to network nodes based on an opinion generation and confidence of the decision. Each time a node receives a message from others it generates an opinion based on the trustworthiness of this message. To calculate this opinion, nodes may consider partial opinions attached to the message, opinions from other nodes (if the sender is known), or a combination of both. Next time this message is forwarded, the new opinion is attached to it. A long-term reputation system for vehicular networking is proposed in [14]. This system provides reliable reputation scores by taking advantages from nodes' daily trajectories. Based on this experience, roadside infrastructure could rely on repeated daily observations of the same set of passing-by vehicles to build long-term reputation scores. To be deployed in a vehicular network, this scheme only requires nodes to have a secret and verifiable certificate. Patwardhan et al. [15] propose a reputation management scheme for VANETs. To evaluate nodes' reputation scores this scheme considers cooperativeness and accuracy of peer-provided data. To calculate these tokens, the proposed scheme uses persistent identifiers, frequency of encounters, and a known set of anchored trustworthy sources to serve as nucleating points for building trust relationships with previously unknown devices. In addition, this scheme deploys an epidemic exchange protocol to ensure high reliability of data and stimulate proactive collaboration between nodes.

In the DTN literature, it is also possible to find several cooperative schemes to stimulate cooperation between network nodes. For example, cooperative ARQ scheme (C-ARQ) [16] tries to reduce the number of loss packets in transmissions between access points placed along roads and vehicles. Same authors propose another cooperative approach called DC-ARQ (delayed cooperative ARQ)

[17]. This scheme is an optimization of the previous one. It realizes cooperation between vehicles until they are out of range of an access point, instead of a packet-by-packet cooperation approach. In [18] authors propose a new cooperative mechanism to encourage nodes to cooperate during a message exchange. To perform such task, this scheme gathers several contributions from a game-theory model. Conducted studies have shown that this cooperative mechanism contributes to a significant improvement of the overall network performance. A study about the impact of misbehavior nodes in DTNs is presented in [19].

Several preliminary studies to enforce cooperation in VDTNs were already conducted [6,7,20]. Most of them try to understand the impact of different cooperative strategies in the overall performance of this type of architecture. This section overviewed the most important contributions already proposed to deal with node reputation and selfish nodes in vehicular networks. All the above-described schemes contributed to the proposal of a reputation system for VDTNs. A preliminary version of a reputation system for VDTNs was presented in [21].

3 Reputation system

This section, divided into two subsections, describes the optimized reputation system proposed for VDTNs focusing on its main features. The first subsection overviews the main features of the reputation system presenting the system operation mode, while the second one details the four reputation mechanisms supported by the system.

3.1 System overview

As above-mentioned, VDTNs use out-of-band-signaling allowing the separation of the control and data planes. The control plane is used to determine and adjust the characteristics of a requested connection in order to ensure a high-quality transmission of the corresponding data bundles. The data plane exchanges data bundles among nodes, according to the contact time scheduled for the data plane. Based on this architectural behavior, a reputation system for VDTNs is proposed to provide a sophisticated tool that allows network nodes to detect, identify, and avoid contacts with selfish or misbehavior nodes. It is expected that a reputation system contributes to an optimization of the overall network performance.

The reputation system operation may be described as follows. At the beginning of its process, each network node initializes a reputation table and a reputation score. The reputation table will store information (e.g., node name and reputation score) about all the encounter nodes. Each time a contact opportunity is available, the encountered node is added to the reputation table (if it does not already exist) and the reputation score is updated using the VDTN out-of-band-signaling at the

control plane phase. At this phase, nodes exchange control information (setup messages), such as node type, geographical location, route, speed, supported link technologies properties, energy status, and buffer status. When the reputation system is active, nodes also exchange their reputation score. Afterwards, the reputation system accepts or denies a contact opportunity based on the nodes' reputation score by comparing it with a network reputation threshold (α), which is equal to all the network nodes and is defined at the beginning of the system execution. Nodes are able to exchange bundles and perform other data plane functions if their reputation score is higher than α . At the end of each contact, the nodes' reputation score is updated based on their performance during the contact opportunity. To update the nodes' reputation score, the reputation system considers two variables: delivered and dropped bundles. Each time a node successfully delivers a bundle to its final destination, it is rewarded with an increase on its reputation score. On the other hand, each time a node drops a bundle without sending it at least one time, it is punished and its reputation score decreases. Each time a node has a reputation score lower than the network reputation threshold, it is marked as a selfish node and is added to a blacklist. Nodes that are presented in the blacklist are ignored.

In the proposed reputation system, the reputation score is not only used to add nodes to the blacklist or to accept or deny a contact opportunity. It is also used to set the node cooperative threshold. The cooperative threshold is used to set the amount of resources that nodes share with others network nodes. For example, if a node has a reputation score equal to 80%, it means that this node will reserve 80% of its buffer capacity to store bundles from others. It also means that this node will spend 80% of an available contact time sending messages from other nodes. With this approach it is

expected that selfish nodes will be identified and isolated soon in order to improve the overall network performance. Figure 1 illustrates the reputation system workflow.

3.2 Reputation system update module

The reputation system update module defines how the reputation score will be updated. To perform such task, the following four different heuristics were created: (i) simple increment simple decrement (SISD), (ii) double increment simple decrement (DISD), (iii) simple increment double decrement (SIDD), and (iv) simple increment message hop decrement (SIMHD).

In the SISD heuristic, each time a node successfully delivers a bundle to its final destination, its reputation score increases k units, where k is a positive constant. By the other hand, each time a node drops a bundle without send it, at least, once, its reputation score decreases k units. This scheme punishes nodes in the same proportion that rewards them. The DISD and SIDD schemes are a variation from this first scheme. The main difference between them is how they reward/punish nodes. In the DISD scheme, nodes increase their reputation in $2k$ units each time a bundle is delivered to its final destination. Contrary to this, the SIDD scheme punishes nodes in $2k$ units each time a bundle is dropped without having been sent once. This scheme will allow to observe if it is most important to reward nodes or to punish them by their selfish behavior.

The SIMHD scheme considers the number of hops between bundle source and the node where the bundle is dropped (without been sent once) to punish nodes. This scheme is more aggressive than the other schemes in penalizing nodes by their selfish behavior. Each time a node drops a bundle without sending it once, its reputation score decreases $2k + h*k$, where h is the number of bundle hops between the source and the current node. The idea behind this scheme is to punish nodes by the effort of previous nodes to deliver bundles.

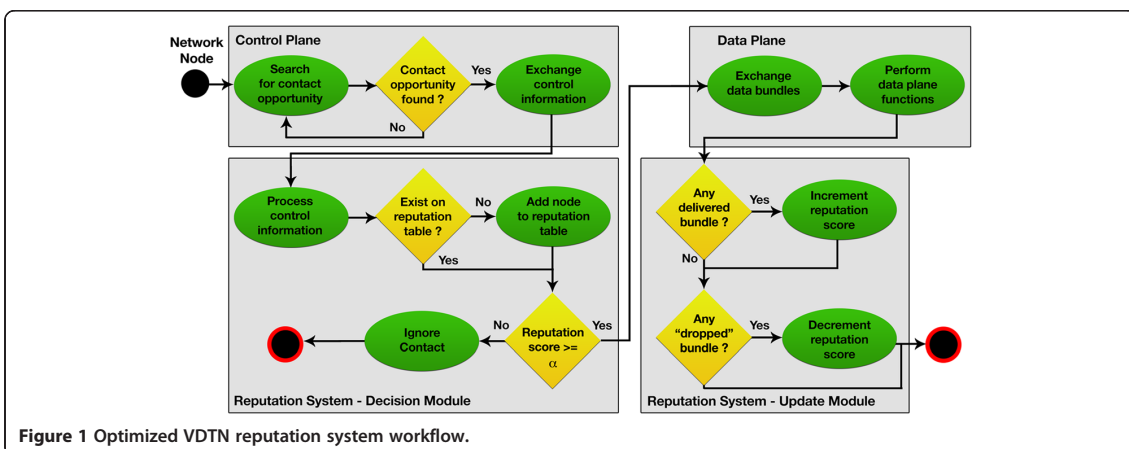


Figure 1 Optimized VDTN reputation system workflow.

4 Simulation setup

This section focuses on the simulation setup considered for the performance evaluation studies. Simulation studies were conducted using the VDTNsim tool [22]. This tool is an extension of the ONE simulator [23,24] and allows simulating the VDTN architectural approach, which comprehends the store-carry-and-forward overlay network below the network layer. This section is divided into three subsections. The first one describes how the urban network scenario was setup, as well as all the corresponding considered parameters. The second subsection elaborates on a rural network scenario presenting the network setup for this scenario, while the third presents the performance metrics and all the routing protocols considered for the performed simulation studies.

4.1 Urban network scenario

For an urban scenario, the simulation considers a map-based model representation of the Dakar region in Senegal, Africa (Figure 2). A cooperative opportunistic environment is considered without knowledge of the traffic matrix and contact opportunities for a period of 24 h. Twenty-seven terminal nodes, acting as traffic sources, represent real-world clinic locations. Each terminal node has a 125-MB (megabyte) buffer and generates bundles using an inter-bundle creation interval in a range of 15 to 30 min, which is uniformly distributed using random values. Each bundle has a size range between 500 KB and 2 MB. All the bundles exchanged in the simulations have an infinite time-to-live (TTL). Their destination address is the terminal node connected to the Internet that acts as the traffic sink.

Seven relay nodes, each one with a 250-MB buffer, are placed at the selected crossroads presented in Figure 2. All the network nodes connect to each other using the standard IEEE 802.11b with a data rate of 6 Mbps and a transmission range of 350 m using omni-directional antennas. Finally, 100 vehicles move along roads with a

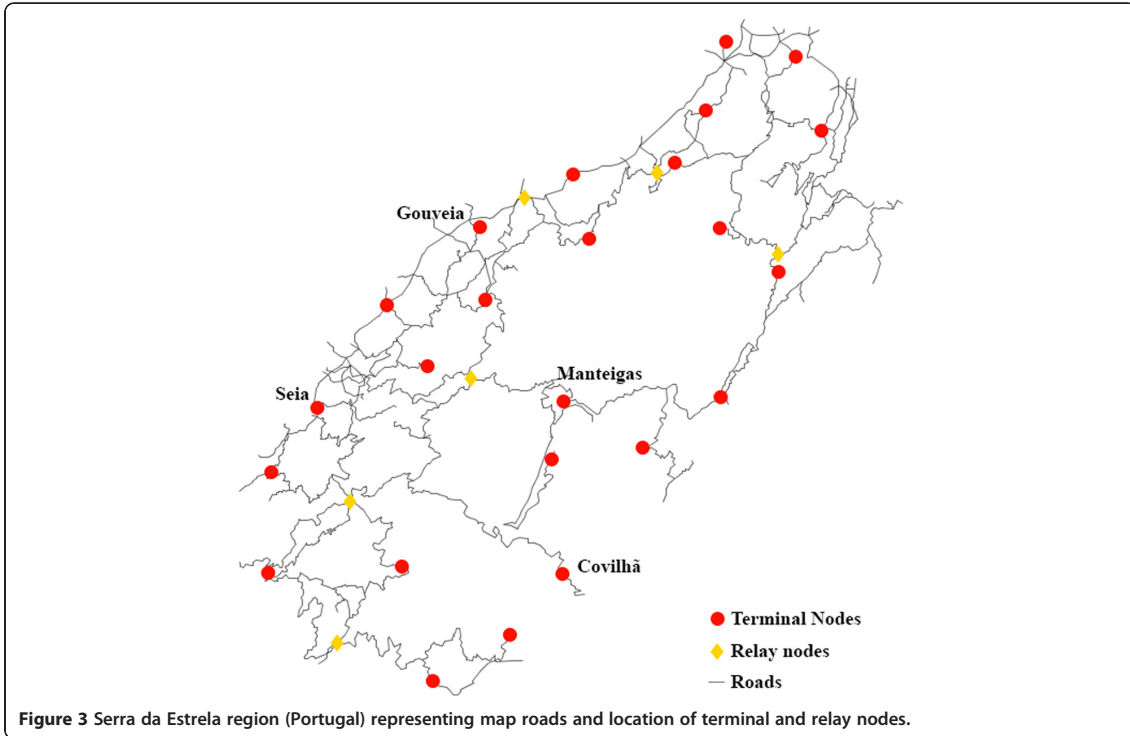
50-MB buffer and at random speed between 30 and 80 km/h. When a vehicle reaches a terminal node, it randomly waits from 15 to 30 min. Then, it randomly selects its next destination node. From these 100 mobile nodes, 25 will act as selfish nodes, receiving bundles from other nodes and dropping them immediately after that. The remaining 75 mobile nodes act as cooperative nodes, sharing their resources depending on their reputation score.

4.2 Rural network scenario

For the rural scenario, the performance experiments consider a real map of Serra da Estrela region, Portugal (Figure 3). In this scenario, 25 terminal nodes acting as traffic source and traffic sink are placed at real-world sparse villages with a buffer capacity of 250 MB. Bundles, with a size ranging from 500 K to 2 MB, are created without TTL with a creation interval in the range of 15 to 30 min. Six relay nodes, with a buffer capacity of 500 MB, are placed at the most important crossroads in order to increase the number of contact opportunities. Contrary to the urban scenario, in this scenario, relay nodes' buffer capacity is increased due to the low density of mobile nodes, which results in fewer contact opportunities between network nodes. With this approach, relay nodes can store a larger number of bundles, in order to increase the bundle delivery probability [25]. Bundles are transported between terminal nodes by 40 mobile nodes, which move along roads with a buffer capacity of 125 MB and a velocity in the range of 30 to 80 km/h. When a mobile node reaches a terminal node, it randomly waits between 15 and 30 min. Thus, a new random terminal node is chosen to be the next destination point. To study the impact of the proposed reputation system, from the 40 mobile nodes, 10 of them will act as selfish nodes. All the network nodes are equipped with the standard IEEE 802.11b interface to allow communications with other nodes and a data rate of 6 Mbps.



Figure 2 Dakar region (Senegal) representing map roads and the location of terminal (clinics) and relay nodes.



4.3 Performance metrics and routing protocols

The performance metrics considered in this study are the bundle delivery probability, the bundle average delivery delay, and the percentage of dropped bundles. The bundle delivery probability (D_p) is defined as the ratio between the number of unique bundles (i.e., it does not count bundle replicas) that have reached the final destination node(s) and the total number of unique bundles that were created at the source node(s). It is calculated according to Equation 1, where D_p is the bundle delivery probability, D_B is the total number of unique delivered bundles, and C_B is the total number of unique created bundles.

The bundle average delivery delay (D_D) is defined as the average time between bundles creation and their delivery. It is calculated according to Equation 2, where D_D is the bundle average delivery delay, Td_i is the time when the bundle i was delivered, Tc_i is the time when the bundle i was created, and D_B is the total number of unique delivered bundles.

The percentage of dropped bundle (P_{DB}) is defined as the ratio between the total number of dropped bundles and the total number of bundles that was created at the source node(s). It is calculated according to Equation 3, where P_{DB} is the percentage of dropped bundles, N_{DB} is

the number of dropped bundles, and N_{CB} is the total number of created bundles.

$$D_p = \frac{D_B}{C_B} \quad (1)$$

$$D_D = \frac{\sum_{i=1}^{D_B} (Td_i - Tc_i)}{D_B} \quad (2)$$

$$P_{DB} = \frac{N_{DB}}{N_{CB}} \quad (3)$$

For all the simulation experiments, the following three routing protocols are considered: First Contact [26], Spray and Wait [27], and GeoSpray [28]. First Contact is a single-copy forwarding routing protocol that maintains at most one copy of a bundle in the entire network. Contrary to the previous protocol, Spray and Wait routing protocol is a flooding-based routing protocol. It limits the number of copies of each bundle in the network. In studies that consider this protocol, the binary version assumes the use of a limited number of copies equals to 5 ($N=5$). With this approach, binary version of Spray and Wait reduces some overhead of the pure epidemic diffusion. GeoSpray is a multiple-copy geographic routing protocol designed specially for VDTNs.

This protocol exploits the mobility of vehicles and the location information provided by position devices (e.g., Global Positioning System), to support routing decision-making process. GeoSpray was designed to perform into sparse scenarios where communication opportunities are sporadic. It also follows a hybrid approach inspired on GeOpps [29] and the binary version of Spray and Wait. GeoSpray and Spray and Wait protocols were chosen because they were the best performing protocols in previous studies focused on cooperation in VDTNs [6].

Across all the experiments, the impact of selfish nodes in the overall performance is evaluated as well as how the reputation system can help to identify and isolate them. Six different reputation thresholds (0, 10, 20, 30, 40, and 50) were studied along the simulation experiments.

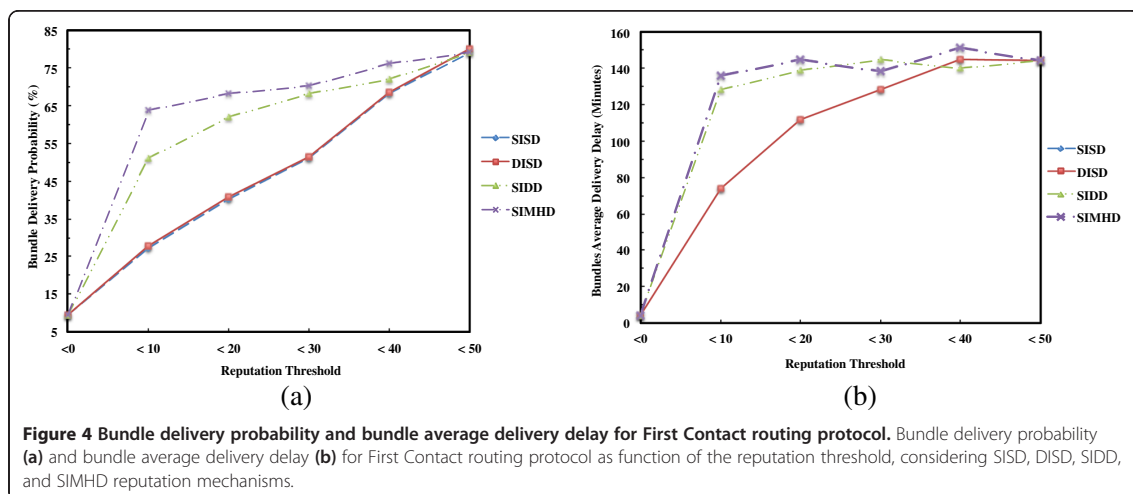
5 Performance analysis of the VDTN reputation system in an urban environment

This section focuses on a deep performance analysis of the above-presented reputation system enforced in an urban environment and its impact on the performance of VDTNs. Considering the presented heuristics used on the reputation system update module presented at the end of the Section 3, this section is divided into four subsections. The impact of the proposed reputation system in a single-copy routing protocol, called First Contact, is presented in the Subsection 5.1. The Subsection 5.2 focuses on the performance of the same reputation system when enforced in Spray and Wait routing protocol, while the Subsection 5.3 presents a discussion about the obtained results for GeoSpray routing protocol. Finally, the last subsection discusses the obtained results for this urban environment.

5.1 Impact of VDTN reputation system on First Contact routing protocol

This study starts with the results observed in simulation experiments with First Contact routing protocol. As this routing protocol is a single-copy forwarding routing protocol, it is very important to select the best nodes to forward bundles in order to increase their delivery probability. The results observed shown the importance of introducing a reputation system to identify selfish nodes in the network. Figure 4a shows that all the considered reputation mechanisms help to reduce the impact of selfish nodes by increasing the number of delivery bundles. The same figure also shows that mechanisms that are more aggressive in penalizing selfish nodes (SIMHD and SIDD) outperform those who do not have this approach (SISD and DISD). More accurately, SIMHD presents gains of approximately 37%, 28%, 19%, and 8% (for cooperation threshold equals to 10, 20, 30, and 40, respectively) when compared to the SISD reputation mechanism. When compared to the DISD mechanism, it presents gains of approximately 36%, 27%, 19%, and 7%. SIMHD and SIDD mechanisms have a very similar performance. However, SIMHD slightly outperforms the performance of SIDD mechanism.

Figure 4b shows the results observed by the same protocol for the bundle average delivery delay. As expected, by identifying and avoiding selfish nodes, the number of available nodes to forward bundles will decrease, which will force bundles to stay more time in nodes buffer and, consequently, it will increase the bundle average delivery delay for routing protocols with a single-copy approach. The SISD approach delivery bundles approximately 62, 33, 10, and 7 min sooner (for cooperation threshold equals to 10, 20, 30, and 40, respectively) when compared to the SIMHD approach.



When compared to the SIDD, the same heuristic delivers bundles approximately 54, 27, 17, and 4 min sooner. The DISD approach delivery bundles approximately at the same time of the SISD approach.

5.2 Impact of VDTN reputation system on Spray and Wait routing protocol

Contrary to First Contact, Spray and Wait is a routing protocol with a flooding approach. This means that each time a bundle is forwarded to a node, the sender node keeps a copy of this bundle on its buffer until the bundle is discarded by buffer congestion. As expected, Spray and Wait performs better than First Contact presenting better delivery probabilities across all the experiments. This assumption is confirmed comparing the results presented at Figures 4a and 5a.

The effect of cooperation, as an effective strategy to increase the bundle delivery probability, is even more pronounced in this routing protocol. Figure 5a shows that when a reputation system considers the SIMHD heuristic, the bundle delivery probability increases approximately 6%, 4%, 2%, and 1% (for cooperation threshold equals to 10, 20, 30, and 40, respectively) comparatively to the SISD approach. When compared to the DISD approach, the SIMHD approach presents gains of 5%, 3%, 2%, and 1%. Finally, when compared to the SIDD, the SIMHD heuristic presents gains of 1%, 1%, 1%, and 1%, respectively.

Contrary to the observed results for First Contact routing protocol (Figure 4b), with the integration of a reputation system, heuristics that aggressively punish nodes deliver bundles sooner (Figure 5b). Comparatively with the SISD, the SIMHD scheme delivers bundles approximately 3, 3, 2, and 1 min sooner (for cooperation threshold equals to 10, 20, 30, and 40, respectively).

When compared to the DISD, the same scheme delivers bundles 2, 2, 1, and 1 min sooner. SIMHD and SIDD have a very similar performance in terms of bundle average delivery delay.

5.3 Impact of VDTN reputation system on GeoSpray routing protocol

As may be seen in Figure 6a,b, GeoSpray has a similar performance in this resource-constrained network scenario, when compared to Spray and Wait. As shown in Figure 6a when nodes follow the SIMHD scheme, the bundle delivery probability increases compared with other schemes. When compared with the SISD scheme, it increases to approximately 9%, 6%, 5%, and 2% (for reputation threshold equals to 10, 20, 30, and 40, respectively). It also performs better than the DISD, by delivering approximately 9%, 6%, 5%, and 2% more (for reputation threshold equals to 20, 30, and 40, respectively). Finally, SIDD delivers 3%, 2%, 2%, and 1% less, respectively, when compared with the SIMHD scheme.

In terms of bundle average delivery delay, the performance of GeoSpray presents significant gains when compared to Spray and Wait. SISD and DISD schemes deliver bundles later and present a similar performance. However, SIMHD delivers bundles approximately 2, 2, 1, and 1 min sooner (for reputation threshold equals to 10, 20, 30, and 40, respectively) when compared to the SIDD scheme. Figure 6b also shows that the bundle average delivery delay tends to decrease as the cooperation threshold value increases.

5.4 Discussion

This subsection overviews and discusses the results obtained for all the conducted studies, considering different reputation mechanisms in an urban environment.

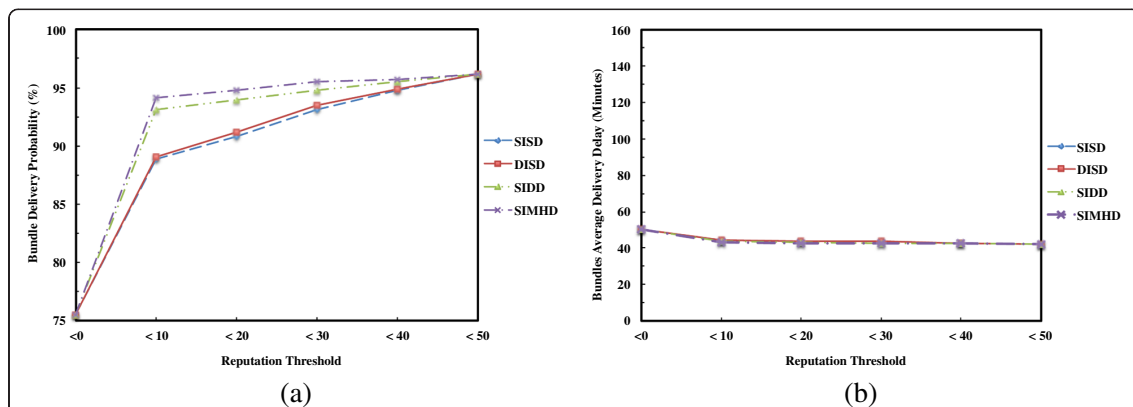
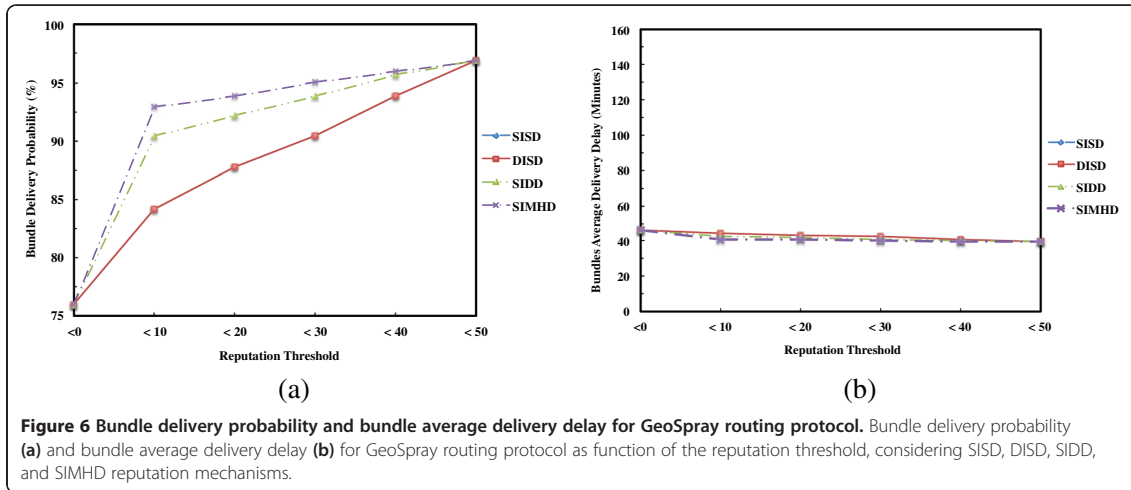


Figure 5 Bundle delivery probability and bundle average delivery delay for Spray and Wait routing protocol. Bundle delivery probability (a) and bundle average delivery delay (b) for Spray and Wait routing protocol as a function of the reputation threshold, considering SISD, DISD, SIDD, and SIMHD reputation mechanisms.



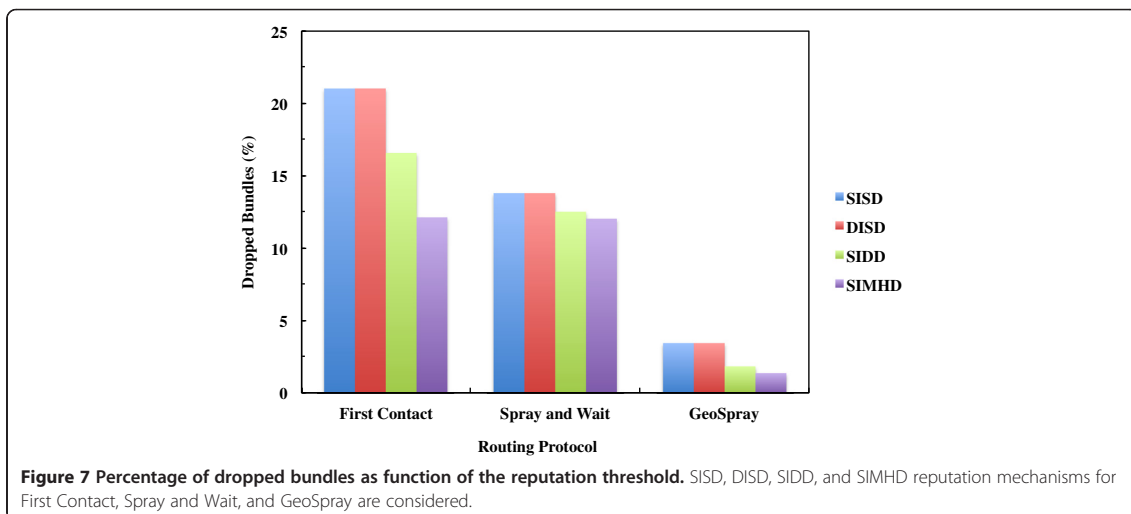
For all the considered routing protocols, reputation functions that penalize selfish nodes in a more aggressive way contribute to improve the overall network performance by increasing the number of delivered bundles. As a consequence of increasing the number of delivered bundles in flooding-based approaches, a decrease of the bundle average delivery delay was observed. This network improvement may also be confirmed taking into account the percentage of dropped bundles for a reputation threshold of 40 (Figure 7).

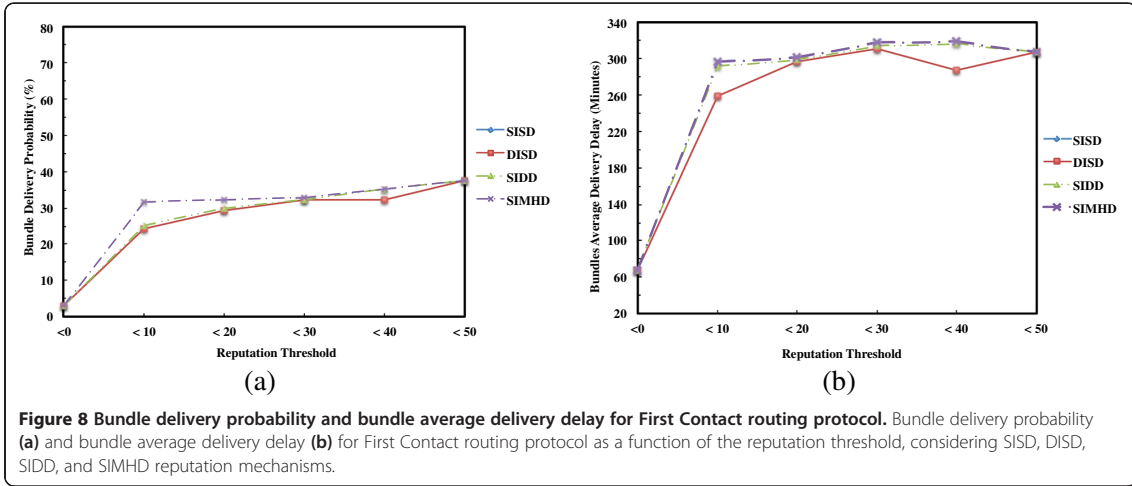
As may be seen in the same figure, GeoSpray presents the lower percentage of dropped bundles. Considering the SIMHD heuristic, it drops 11% less of the bundles when compared to the Spray and Wait routing protocol, and 12% of the bundles when compared to the First

Contact routing protocol. Regarding the SIDD approach, GeoSpray drops less 11% of bundles when compared to the same heuristic when enforced on the Spray and Wait routing protocol. When compared to First Contact, GeoSpray drops 15% less considering the SIDD heuristic. The other two heuristics (SIRD and DISD) have a similar performance in all the considered routing protocols. However, when applied to GeoSpray, it drops 11% less of the bundles when compared to Spray and Wait and 18% when compared to First Contact.

6 Performance assessment of the VDTN reputation system in a rural environment

This section presents the observed results when proposed VDTN reputation system is enforced on a rural





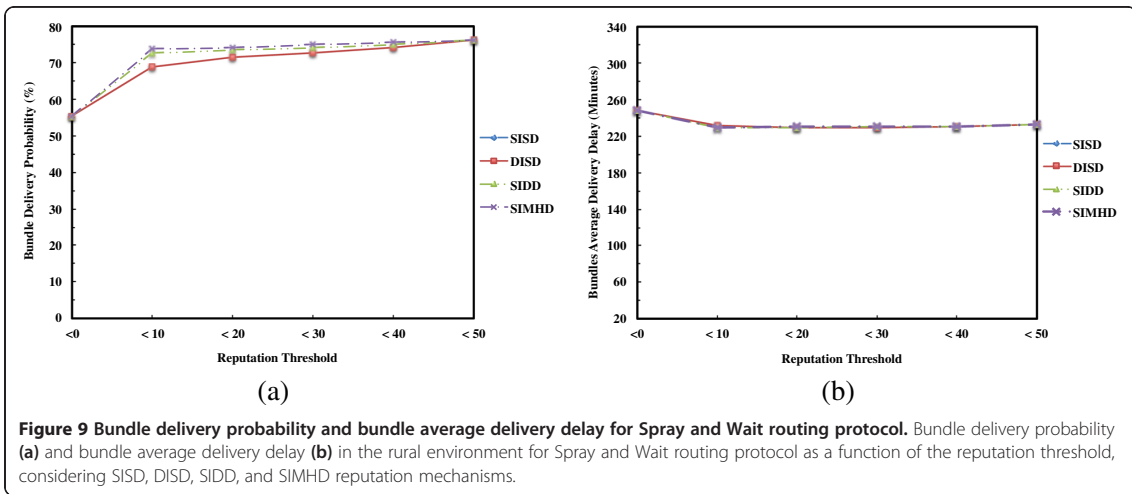
environment. Following the same approach of the previous section, this section considers four subsections. It starts to present the observed results for the First Contact routing protocol. Afterwards, the performance of the same reputation system when enforced in Spray and Wait and GeoSpray routing protocols is studied. Finally, several considerations are fixed about the conducted studies in a rural environment.

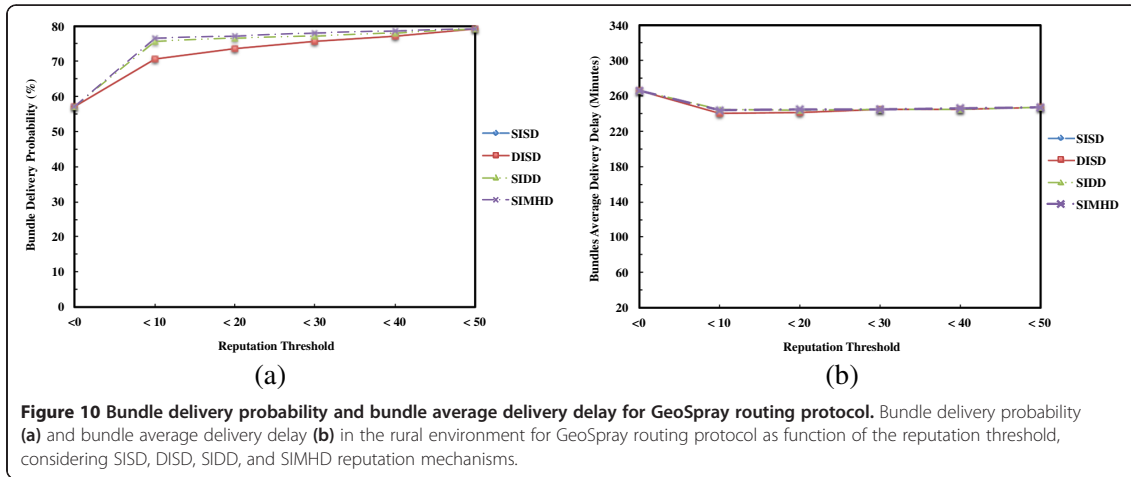
6.1 Impact of VDTN reputation system on First Contact routing protocol

The results observed for the First Contact confirm those obtained for the urban scenario. Introducing a reputation system to detect, identify, and avoid selfish nodes contributes to increase the bundle delivery probability (Figure 8a). The SIMHD heuristic presents gains of

approximately 8%, 3%, 1%, and 3% (for cooperation threshold equals to 10, 20, 30, and 40, respectively) when compared to the SISD reputation mechanism. When compared to the DISD mechanism, it presents gains of approximately 7%, 3%, 1%, and 2%, while the SIDD heuristic delivers approximately 6%, 2%, 1%, and 1% less bundles.

Figure 8b shows the results observed by the same protocol for the bundle average delivery delay. As expected, the bundle average delivery delay for this routing protocol increases as the reputation threshold increases. The SISD approach delivery bundles approximately 38, 4, 7, and 32 min sooner (for cooperation threshold equals to 10, 20, 30, and 40, respectively) when compared to the SIMHD approach. When compared to the SIDD, the same heuristic deliver bundles approximately





33, 2, 3, and 29 min sooner. The DISD approach delivery bundles approximately at the same time of the SISD approach.

6.2 Impact of VDTN reputation system on Spray and Wait routing protocol

As expected, Spray and Wait performs better than First Contact not only in terms of bundle delivery probability but also in terms of bundle average delivery delay. Figure 9a shows that when a reputation system considers the SIMHD heuristic, the bundle delivery probability increases approximately 5%, 3%, 2%, and 1% (for cooperation threshold equals to 10, 20, 30, and 40, respectively) comparatively to the SISD approach. When compared to the DISD approach, the SIMHD approach presents gains of 4%, 2%, 2%, and 1%. Finally, when compared to the SIDD, the SIMHD heuristic present gains of 1%, 1%, 1%, and 1%, respectively.

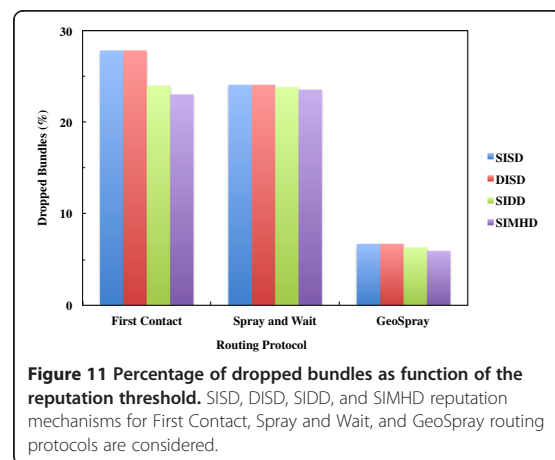
Contrary to the single-copy approach, with the integration of a reputation system, heuristics that aggressively punish nodes deliver bundles sooner in Spray and Wait (Figure 9b). Comparatively with the SISD, the SIMHD scheme delivers bundles approximately 2, 1, 1, and 1 minute sooner (for cooperation threshold equals to 20, 30, and 40, respectively). When compared to the DISD, the same scheme delivers bundles 1, 1, 1, and 1 min sooner. SIMHD and SIDD have a very similar performance in terms of bundle average delivery delay.

6.3 Impact of VDTN reputation system on GeoSpray routing protocol

GeoSpray has a similar performance when compared to Spray and Wait in this resource constrained network scenario. Figure 10a shows that when nodes follow the SIMHD scheme, the bundle delivery probability increases when compared with other schemes. When

compared to the SISD scheme, it presents gains of approximately 6%, 4%, 2%, and 2% (for reputation threshold equals to 10, 20, 30, and 40, respectively). It also performs better than the DISD, by delivering approximately 6%, 4%, 2%, and 2% more (for reputation threshold equals to 20, 30, and 40, respectively) of the bundles. Finally, SIDD delivers 1%, 1%, 1%, and 1% less of the bundles, when compared with the SIMHD scheme.

In terms of bundle average delivery delay, the performance of GeoSpray presents significant gains when compared to Spray and Wait. SISD and DISD schemes deliver bundles later and present a similar performance. However, SIMHD delivers bundles approximately 1, 1, 1, and 1 min sooner (for reputation threshold equals to 10, 20, 30, and 40, respectively) when compared to the SIDD scheme. Figure 10b also shows that the bundle average delivery delay tends to decrease as the cooperation threshold value increases.



6.4 Discussion

In a rural environment, where the number of contact opportunist is sparse, it is very important to forward bundles to nodes that are able to deliver them. It was shown that a reputation system that punishes nodes by their selfish behavior contributes to improve the overall network performance. Although the results presented in the previous subsections, this network improvement may also be confirmed, taking into account the percentage of dropped bundles for a reputation threshold of 40 (Figure 11).

From all the considered routing protocols, GeoSpray is the one that presents the lower percentage of dropped bundles. Considering the SIMHD heuristic, it drops less 18% of the bundles when compared to the Spray and Wait routing protocol, and 17% of the bundles when compared to the First Contact routing protocol. Regarding the SIDD approach, GeoSpray drops less 18% of the bundles when compared to the same heuristic when enforced on the Spray and Wait routing protocol. When compared to First Contact routing protocol, GeoSpray drops less 18% considering the SIDD heuristic. The other two heuristics (SISD and DISD) have a similar performance in all the considered routing protocols. However, when applied to GeoSpray, it drops less 17% of the bundles when compared to Spray and Wait and 21% when compared to First Contact.

7 Conclusions

In the last years, vehicular architectures have been the focus of research not only by the scientific community but also by the automotive industry. VDTNs have been proposed as a possible solution to overcome the most challenging issues of vehicular communications. However, VDTNs still face several challenges on data communications due to sparse and intermittent connectivity or even the absence of an end-to-end path between the source and destination nodes.

This paper focuses on nodes' cooperation and how selfish nodes may influence the overall network performance. To reduce the impact of such nodes, an optimized version of a VDTN reputation system was proposed and enforced on VDTNs. This system includes four different ways to reward/punish nodes, and their performance was evaluated considering three different protocols (First Contact, Spray and Wait, and GeoSpray). It was shown that schemes that penalize selfish nodes in a more aggressive way contribute to increase the overall network performance (the number of delivered bundles increases and the number of dropped bundles decreases). This can be observed by the significant increase of the performance of First Contact routing protocol. From the two considered flooding-based routing protocols, GeoSpray has the best performance. Comparing the observed results for Spray and Wait and GeoSpray with the performance results in [21] for the same routing

protocols, we can conclude that the reputation system improvement contributes to an increase of the bundle delivery probability. This was accomplished through the implementation of a more accurate function to calculate nodes' cooperative threshold.

This work may be used as a base to develop more complex reputation strategies that contribute to an increase of the overall network performance. Monitoring and management strategies may also be developed to help nodes in saving network resources. Mechanisms to incentive selfish nodes to cooperate in order to reactivate them to be considered in the network may also be proposed. All the above-presented proposals may be suggested for further research works.

Competing interests

The authors declare that they have no competing interests.

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Author details

¹Instituto de Telecomunicações, University of Beira Interior, Covilhã 6201-001, Portugal. ²Guangdong University of Petrochemical Technology, Guangzhou 51000, China. ³CISTER Research Center, ISEP, Polytechnic Institute of Porto (IPP), Porto 4200-135, Portugal.

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Chapter 6

A Cooperative Watchdog System to Detect Misbehavior Nodes in Vehicular Delay-Tolerant Networks

This chapter is based on the following paper:

A Cooperative Watchdog System to Detect Misbehavior Nodes in Vehicular Delay-Tolerant Networks

João A. F. F. Dias, Joel J. P. C. Rodrigues, Feng Xia, and Constandinos X. Mavromoustakis

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Journal Ranking (2015): 1/56 (Instruments & Instrumentation)



A Cooperative Watchdog System to Detect Misbehavior Nodes in Vehicular Delay-Tolerant Networks

João A. F. F. Dias, Joel J. P. C. Rodrigues, *Senior Member, IEEE*, Feng Xia, *Senior Member, IEEE*, and Constandinos X. Mavromoustakis, *Senior Member, IEEE*

Abstract—In vehicular delay-tolerant networks (VDTNs), an end-to-end relay path between bundle source and destination nodes may not be available. To accomplish such goal, VDTNs rely on nodes cooperation. Thus, in order to maintain network efficiency, it is very important to ensure that all network nodes follow the protocol. This is not an easy task since nodes may diverge from the protocol due to a selfish behavior or to maintain their data or resources integrity. This paper proposes a cooperative watchdog system to detect and act against misbehavior nodes in order to reduce their impact in the overall network performance. Its operation relies on a cooperative exchange of nodes reputation along the network. By detecting selfish or misbehaving nodes, it is possible to improve the overall network performance. Conducting simulation experiments considering the VDTNSim tool and the Spray-and-Wait routing protocol shows that the cooperative watchdog proposed for VDTNs is not only effective in detecting misbehaving nodes but also contributes to improve the overall network performance by increasing the bundle delivery probability and decreasing the amount of resources waste.

Index Terms—Cooperation, performance evaluation, selfish nodes, vehicular delay-tolerant network (VDTN), watchdog.

I. INTRODUCTION

VEHICULAR delay-tolerant networks (VDTNs) [1] were proposed as new kind of vehicular networks, whose design supports communications in environments where an end-to-end path between the source and destination may not be

available. Like other ad hoc networks [2]–[4], VDTNs rely their operation on cooperation between mobile nodes (e.g., vehicles), which are exploited to store-carry-and-forward bundles. VDTNs consider three kinds of nodes: mobile, terminal, and relay nodes. Mobile nodes move along paths and may interact with the other two types of VDTN nodes. Terminal nodes are usually placed at the edge of the VDTN network and are responsible for the heavy data processing and interaction with other networks (such as the Internet), whereas relay nodes are placed at road intersections increasing the number of network contacts and storing a higher number of bundles that can be picked by any passing-by vehicle. Contrary to other vehicular networks, in VDTNs, each contact opportunity is processed in two phases: control plane and data plane phases (performing out-of-band signaling). At the beginning of a contact opportunity (using the control plane) nodes exchange signaling information (e.g., speed, buffer status, destination node) in order to setup and reserve resources for an appropriate transmission of data bundles at the data plane. In the data plane, datagrams are aggregated into bundles and forwarded to a single or multiple destination nodes. This out-of-band signaling approach offer the possibility to use different network technologies in each plane and improves the overall network performance since nodes, based on the signaling information, may decide to reject a contact opportunity in order to save resources or to prevent data from being compromised. Although all the already achieved improvements, VDTNs still dealing with the presence of misbehavior nodes that do not follow the protocol and severely affect the overall network performance. Usually, this kind of nodes exploits and consumes other nodes resources serving only their purposes. For example, a node that drops bundles without sent them at least once may be classified as a selfish node. This kind of nodes also leads to a huge waste of network resources, and may compromise the performance of well-behaved nodes. This situation makes very important to detect and take some kind of action against such nodes. However, this is a challenged task due to the high mobility of vehicles that increases the ambiguity of their detection and classification. A possible solution for this problem is to afford nodes with sophisticated mechanisms that can detect and avoid nodes with suspicious behavior.

In this paper, a cooperative watchdog system (CWS) is proposed to support network nodes to detect selfish nodes. To perform such task, CWS assigns a reputation score to each network node. Thus, each time nodes participate in a

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J. A. F. F. Dias is with the Instituto de Telecomunicações, University of Beira Interior, 6201-001 Covilhã, Portugal (e-mail: joao.dias@it.ubi.pt).

J. J. P. C. Rodrigues is with the Instituto de Telecomunicações, University of Beira Interior, 6201-001 Covilhã, Portugal, and also with King Saud University, Riyadh 12372, Kingdom of Saudi Arabia (e-mail: joelj@ieee.org).

F. Xia is with the School of Software, Dalian University of Technology, Dalian 116620, China (e-mail: f.xia@ieee.org).

C. X. Mavromoustakis is with the Department of Computer Science, University of Nicosia, 1700 Nicosia, Cyprus (e-mail: mavromoustakis.c@unic.ac.cy).

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contact opportunity, the CWS updates their reputation score based on the considerations of three modules (classification, neighbor's evaluation, and decision). The classification module aims to categorize nodes into different types, according to their reputation score. Founded on their categorization, the classification module calculates each node's cooperative value. The cooperative value is then transmitted to the decision module in order to punish or reward nodes in function of their cooperative behavior. The neighbor's evaluation module determines how neighbors evaluate a node's reputation on the network. This is accomplished by asking them their opinion about it. At the end of a contact opportunity, the decision module updates the nodes' reputation score based on the information transmitted by the other modules. With this approach, the CWS manages to classify, monitor, and act against such kind of nodes. When a selfish node is detected, the CWS sends an alarm to all of the node's neighbors in order to be spread by the entire network. This alarm will inform cooperative nodes of the presence of a new selfish node. Then, the main contributions of this paper are the following:

- an overview regarding the most important credit-based and reputation-based approaches for cooperative communications in vehicular networks;
- a case study presenting the negative impact of selfish nodes in the performance of VDTNs considering as performance metrics the bundle delivery probability, bundle average delay, overhead ratio, and number of dropped bundles;
- proposal of a CWS composed by three distinct modules that aims to detect and avoid selfish nodes in order to reduce their impact on the performance of cooperative nodes;
- performance studies to evaluate the impact of the proposed cooperative watchdog solution on the performance of VDTNs considering the bundle delivery probability, bundle average delay, overhead ration, and number of dropped bundles.

The remainder of this paper is organized as follows. Section II presents an overview about available methodologies used to incentive nodes to cooperate or to detect misbehavior nodes. A case study to demonstrate the impact of selfish nodes in a VDTN network is presented in Section III. Section IV introduces the main concepts of the cooperative watchdog model and its implementation in VDTNs. Experimental evaluation results are presented in Section V, whereas Section VI concludes the paper and presents several guidelines for further research works.

II. RELATED WORK

In the last years, communications among vehicles have attracted significant attention from the automotive and research community [5]–[12]. For this reason, cooperation among nodes became an important concern, and several approaches were proposed to encourage them to cooperate. Most of the work already proposed to deal with cooperation in vehicular communications follow the Mobile Ad Hoc Networks [4] approach, which

classifies cooperation approaches into two main categories: credit-based [13]–[17] and reputation-based [18]–[22]. The credit-based methodology follows the idea that network nodes should use a virtual currency to consume network resources. For example, nodes must pay to get or use network resources, and are paid to provide or share them with other network nodes. On the other hand, reputation-based mechanisms use a monitoring approach to detect misbehavior nodes. After that, they spread an alarm through the network in order to inform other nodes about the presence of this kind of nodes. Nodes use this alarm to avoid or perform some action (e.g., punish or encourage) against selfish or misbehavior nodes. This section overviews and discusses the most important contributions in both cooperative methodologies for vehicular networks, considering them separately into credit-based and reputation-based approaches.

A. Credit-Based Proposals

Haigang *et al.* [23] propose a routing protocol for vehicular networks called SCR. This routing protocol bases its performance on a social contribution concept, and it is prepared to deal with selfish or misbehavior nodes. To make forward decisions, SCR considers two different variables: delivery probability and social contributions of a network node. Nodes delivery probability is calculated based on the social relations between nodes, whereas the social contribution is determined based on reciprocal and community contributions. The social contribution is used to incentive selfish nodes to cooperate and share their resources with others.

VIME [24] is an economic incentive model created to combat selfish and misbehavior nodes. Initially, this model gave a certain number of credits to network nodes that will be used by them to forward messages to other network nodes. Each time a node sends a message, it pays a certain cost that will be used by the receptor to confirm the truthfulness of the information. In order to earn credits and continue to be seen as a cooperative node in the network, nodes have to cooperate with each other.

FRAME [25] is an incentive scheme that aims to stimulate cooperation in VANETs. This scheme implements two different mechanisms to reward nodes for their cooperative behavior: weighted and sweepstake. The weighted mechanism considers the unique characteristics of VANETs to assign weight rewards to network nodes in exchange of their contributions. The sweepstake mechanism guaranties a fixed payment to the node that delivers a message to its final destination. This strategy tries to encourage nodes to avoid intermediate nodes and get connected directly with the destination node.

Tingting *et al.* [26] proposed an incentive scheme for VANETs that considers a coalitional game theoretic approach. In this scheme the core of the coalitional game is to follow the protocol. When nodes do not have enough space to storage more messages, the scheme offers them the possibility to discard some messages from the buffer without any punishment. Contrary to other proposals, this scheme considers incentives to all network nodes (including source nodes) and guarantees node cooperation using rigorous theoretical analysis.

SMART [27] is a credit-based incentive scheme for DTNs that aims to stimulate network nodes cooperation in order to forward a higher number of bundles. To accomplish this goal SMART implements several rewarding techniques. For example, nodes may be rewarded each time they send a packet or each time they successfully deliver a bundle before its time-to-live (TTL) expires. SMART is also prepared to deal with several selfish node attacks. For example, SMART can deal with credit forgery, nodular tontine, and submission refusal attacks. Similar to this scheme, a credit-based incentive system for DTNs, called MobiCent, was proposed in [28]. This system aims to discover the most efficient path between the source and destination nodes. In order to achieve this goal, MobiCent implements incentive mechanisms that are used as an encouragement approach to minimize data delivery and payment process delay.

B. Reputation-Based Approach

A fuzzy reputation system [29] for VANETs was proposed to encourage packets forwarding and control misbehavior nodes. To control selfish nodes this scheme considers two components: a forward manager and a fuzzy reputation manager. The forward manager controls the number of received forwarding requests and the number of packets forwarded by the node where it is running. The reputation manager is used to detect if other nodes are selfish or cooperative. Packets sent by selfish nodes are eliminated from the network.

In [30], a reputation-based announcement scheme was proposed. This scheme takes advantages of a reputation system to evaluate message reliability. The reliability of a message is determined based on the vehicle reputation score that generates this message. A message is only marked as reliable if the source node has a high reputation score. To determine a vehicle reputation score, the feedback from other vehicles about the reliability of its messages is considered. This score is constantly collected and updated. Its trustiness is achieved using a trusted party.

Park *et al.* [31] proposed a long-term reputation system that relies its performance on the roadside infrastructure's daily observations. This system uses repeated daily observation of passing-by vehicles to determine vehicles reputation scores. To accomplish this goal, the system requires that vehicles have a secret and a verifiable certificate. Similar to this solution, it is the approach followed by vehicle ad hoc network reputation system [32]. With this system every network node has a reputation score that is determined by an opinion generation. To generate this opinion nodes can consider one of the following approaches: i) partial opinions from other nodes attached to messages; ii) opinions from other network nodes; and iii) combination of both.

More recently, a reputation system [33] for VDTNs was proposed. This system considers a reputation threshold to classify mobile nodes into selfish or cooperative nodes. If a node reputation score is higher than the reputation threshold it is marked as a cooperative node; otherwise, it is marked as a selfish node. Four different strategies were implemented to reward or punish nodes by their performance in the network. For example,

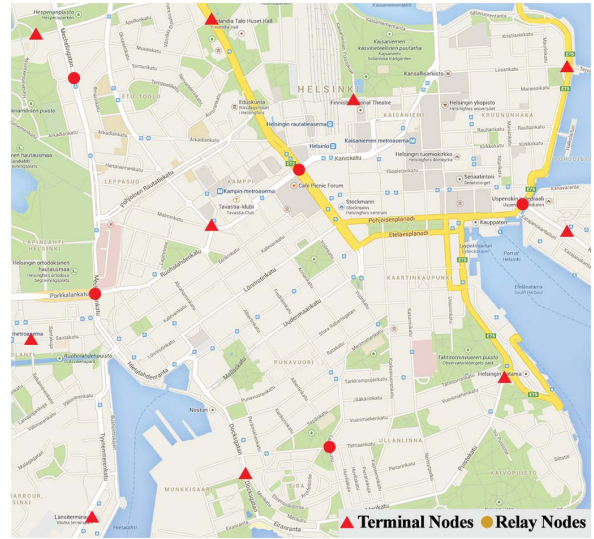


Fig. 1. Illustration of the considered map-based representation of Helsinki, Finland, with the location of terminal nodes and the stationary relay nodes.

each time a node delivers a message to its final destination, its reputation score increases. On the other hand, this system decreases nodes reputation score if they drop messages without sending them, at least, once.

III. PROBLEM STATEMENT

This paper addresses the problematic of misbehavior nodes that contributes to the network performance degradation when no action is taken against them. In order to show the impact of such kind of nodes in the performance of VDTNs, a case study was conducted using the VDTNSim [34] simulation tool. The simulation scenario includes a map-based representation (with 4500×3400 square meters) considering part of Helsinki, Finland (see Fig. 1). During a simulation time of 24 h, all network nodes communicates using IEEE 802.11b (at 6 Mbps), and a transmission range of 350 m using omnidirectional antennas. Ten terminal nodes, each one with 100 MB (MegaBytes) of buffer capacity, act as traffic source and traffic sinks. To increase the number of network contacts, 5 relay nodes were placed at five road intersections, as shown on Fig. 1. Each relay node has a buffer capacity of 200 MB. A set of mobile nodes, varying from 30 to 100, moves along map roads with an average speed of 50 Km/h and a buffer capacity of 50 MB. Across all simulations (30 for each point) the percentage of selfish nodes starts on 0% (without selfish nodes) and increase gradually up to 50% of the total number of nodes. To better understand their impact on the network, none selfish nodes detection mechanisms were considered.

The study starts with an analysis of the impact of selfish nodes on the percentage of delivered bundles [see Fig. 2(a)]. As may be seen, as the number of selfish nodes increases, the number of delivery bundles decreases significantly. Such behavior proves the importance of detecting these nodes in order to perform some action against them (e.g., punish or

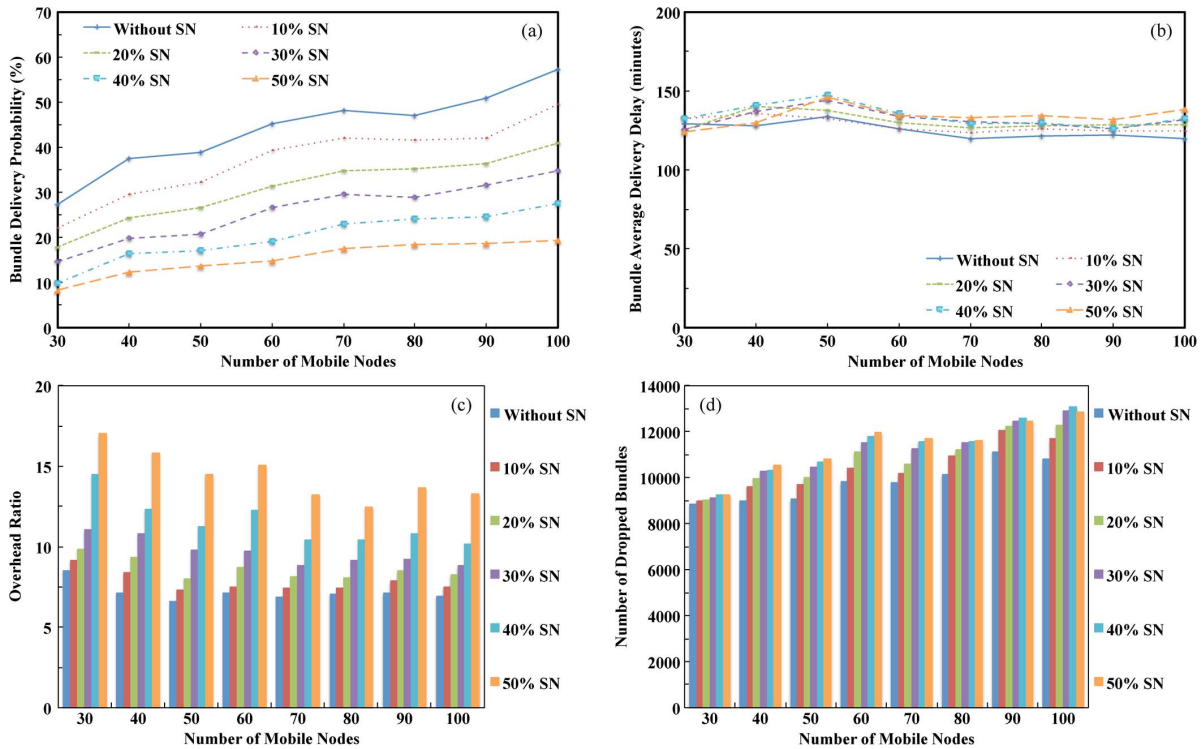


Fig. 2. Impact of selfish nodes on the (a) bundle delivery probability, (b) bundle average delivery delay, (c) overhead ratio, and (d) number of dropped bundles.

exclude from the network). The impact of selfish nodes is also observed on the time that bundles need to arrive to their final destination. This happens because selfish nodes force cooperative nodes to double their efforts to delivery bundles. For example, cooperative nodes will have to carry bundles for a longer period of time until they are delivered to their final destination or to another cooperative node. This process will increase the time that a bundle needs to travel between its source and destination nodes [see Fig. 2(b)]. By keeping bundles for a longer period of time on nodes buffers leads to buffer congestion, which results on a larger number of dropped bundles since nodes must keep their cooperative behavior in order to do not diverge from the protocol. Nodes may also drop bundles in order to save their own resources and data integrity.

The presence of selfish nodes in the network not only affects other nodes but also has a huge impact in the routing protocol. Fig. 2(c) shows the results observed for the overhead ratio, which represent the bandwidth efficiency of a routing protocol. As may be seen, the presence of selfish nodes in the network contributes to a significant increase of the routing protocol overhead ratio, leading to a poor network performance. Fig. 2(d) shows the amount of bundles drooped in consequence of the presence of selfish nodes, and confirms the results observed in Fig. 2(c).

As observed through this section, the consequences that selfish nodes bring to the network may result in a catastrophic scenario. For this reason, it is very important to endow nodes

with sophisticated models to detect and avoid any misbehaving node. For this reason, a CWS for VDTNs is proposed to deal with the presence of such kind of nodes in the network.

IV. CWS

This section presents the main features of the CWS proposed for VDTNs. The CWS main goal is to afford VDTNs network nodes with a sophisticated mechanism to detect nodes that are diverging from the protocol.

A. Main Principles

With the CWS, each network node has a reputation score (α), which will be used to set the percentage of resources that nodes may share with others (e.g., buffer space to store bundles from others or contact time spend to forward bundles from others). Initially, this score is equal to 50 and during the time it may changes between 0 and 100. To update and assign such score, CWS takes advantages of the VDTN out-of-band signaling [1]. At each contact, opportunity nodes exchange information (at the control plane) about their performance through the network (e.g., number of relayed, dropped, and delivered bundles), which will allow them to evaluate each other. This information is also collected by CWS that will keep records containing the performance of each network node. Then, at each contact opportunity, the CWS updates each participating node reputation score considering three different scores:

TABLE I
 κ VALUE ACCORDING TO NODES CATEGORIZATION

Node Type	Reputation Score (α)	κ
Cooperative	$\alpha > 80$	1
Partial Cooperative	$55 < \alpha \leq 80$	0.5
Neutral	$45 < \alpha \leq 55$	0
Suspected	$20 \leq \alpha \leq 45$	-0.5
Selfish	$\alpha < 20$	-1

node reputation score observed by the node itself (RS_I), node reputation score observed by neighbors (RS_N), and a cooperative value assigned by the watchdog (CV_W). To calculate these scores the CWS deploys three different modules: classification module, neighbor's evaluation module, and decision module.

B. Classification Module

The main goal of the classification module is to classify nodes according to their impact on the overall network performance. To perform such task, this module manages a classification table containing a record for each network node, which is updated at each contact opportunity. Each record contains an ID that identifies a node, the last reputation score calculated by the CWS, and its respective cooperative value (CV_W). A node n cooperative value is determined by (1)

$$CV_{W_n} = \beta \cdot \gamma_n \quad (1)$$

where β represents the node performance coefficient and γ represents the punctuation that the classification module gives to node n . The node performance coefficient is a value that represents how node is performing across the network. To calculate such value, the classification module uses (2), where R_{B_i} represents the number of relayed bundles from node i , D_{B_i} represents the number of bundles that node i already delivered, and Dp_{B_i} represents the number of bundles that node i already dropped. Then, this value is normalized to an interval between $[0, 1]$ considering (3). The punctuation enforced by the classification module to nodes (γ) is calculated based on nodes categorization. Nodes may be classified into 5 types considering their reputation score. To calculate γ (4) is considered, where κ is a constant value, which value results from the observation of nodes reputation score (Table I), and λ is a constant defined by the CWS as the measure for reward/punish nodes by its cooperative behavior

$$x = \frac{\sum_{i=1}^N (R_{B_i} - D_{B_i})}{\sum_{i=1}^N (R_{B_i} - Dp_{B_i})} \quad (2)$$

$$\beta = \frac{x - \min(x)}{\max(x) - \min(x)} \quad (3)$$

$$\gamma_n = \kappa \cdot \lambda, \text{ where } \kappa \text{ and } \lambda = \text{constant values.} \quad (4)$$

C. Neighbor's Evaluation Module

The neighbor's evaluation module aims to calculate the RS_N of each node. To calculate such value [(5) and Algorithm 1],

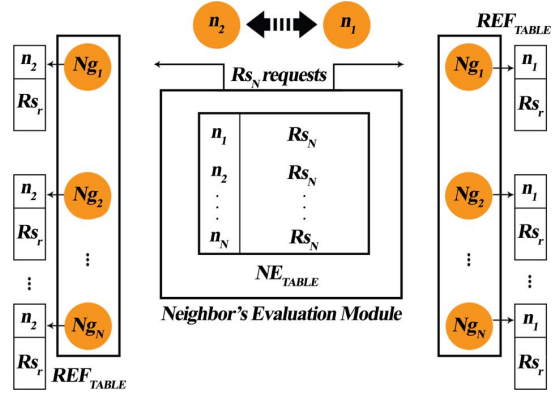


Fig. 3. Illustration of how the RS_N of each node is calculated by the neighbor's evaluation module.

this module builds a table (NE_{TABLE}) containing a record for each network node. Each record contains a node ID and its corresponding RS_N value. At each contact opportunity, the neighbor's evaluation module requests to N neighbors (Ng) to share their opinion about the participating nodes. These neighbors answer to the neighbor's evaluation module request with the node corresponding RS_N value. This value is stored at the referee table (REF_{TABLE}) that each neighbor must maintain during the time it stays on the network. The RS_N value of a node n is updated each time a neighbor is in direct contact with n . Fig. 3 illustrates the operation performed by the neighbor's evaluation module at each contact opportunity

$$RS_N(n) = \frac{\sum_{i=1}^N RS_{R_i}}{N} \quad (5)$$

Algorithm 1: Neighbors observation score (RS_N)

Input: N neighbors to evaluate node n
Output: RS_N of node n
1 opinion := 0
2 **foreach** node $\in N$ **do**
3 opinion := opinion + node _{n} (RS_N)
 $RS_N := \text{opinion} / N$

D. Decision Module

To update the reputation score (α) of a network node at the end of a contact opportunity, the decision module takes into consideration the information transmitted by the classification module (CV_W), the neighbor's evaluation module (RS_N), and the reputation score observed by the node itself (RS_I). The RS_I is collected by an interface that communicates with the VDTN reputation system [33] implemented on each network node. This reputation system allows nodes to formulate an opinion about their own performance. Collected all three scores, the new node reputation score (α_n) is calculated as follows:

$$\alpha_n = \theta \cdot RS_{I_n} + (1 - \theta) \cdot RS_{N_n} + CV_{W_n} \quad (6)$$

where θ is a value ranging between $[0, 1]$ representing how much the CWS trust on nodes observations about themselves. After recalculating nodes α , the decision module transmits both nodes reputation score to the classification module, which

TABLE II
SIMULATION PARAMETERS

Parameter	Value
N° of Terminal nodes	10
Terminal nodes buffer	100 MB
N° of Relay nodes	5
Relay nodes buffer	200 MB
N° of mobile nodes	30, 40, 50, 60, 70, 80, 90, 100
Mobile nodes buffer	50 MB
Average Speed	50 km/h
% Selfish nodes	10%, 20%, 30%, 40%, 50%
Bundles generation interval	[25, 35] seconds
Bundles size	[50, 750 KB]
Bundles time-to-live (TTL)	360 minutes
λ	5
θ	0.8
N	3

update its classification table. The CWS also informs nodes about their new reputation scores. When a node reputation score is below 20 it is marked as a selfish node. This fires an alert that is sent to nodes neighbors in order to spread it across the network. Receiving an alert from the CWS means that some node as been marked as selfish node and must be added to the nodes blacklist. Nodes in the blacklist are ignored and discarded from the network.

V. PERFORMANCE ASSESSMENT

Here, the proposed cooperative watchdog is widely assessed and its performance is analyzed. The main purpose of this study is to evaluate the impact of the proposed watchdog to improve selfish nodes detection when they are present in the network, and how it contributes to improve the overall network performance. To perform such study the binary version of the Spray-and-Wait [35] routing protocol is considered.

A. Simulation Parameters and Performance Metrics

The CWS was deployed in the same network conditions of the case study described on Section III. With the same conditions, it is possible to compare the overall network performance when the CWS is considered with a scenario where no selfish nodes detection is performed. All the parameters of the simulation scenario are summarized in Table II.

Performance metrics considered to evaluate CWS were the bundle delivery probability, its average delivery delay, the introduced overhead ratio, and the number of dropped bundles. The bundle delivery probability was calculated as the ratio between the number of unique bundles that have been forward until they attain their final destination and the number of unique bundles that were created at sources nodes. This metric is calculated according to (7), where B_D is the bundle delivery probability, NT_{DB} is the total number of unique delivered bundles, and NT_{CB} is the total number of created bundles

$$B_D = \frac{NT_{DB}}{NT_{CB}}. \quad (7)$$

The bundle average delivery delay is measured as the average period of time that bundles need to travel from source to destination. (8) shows how this metric is calculated, where

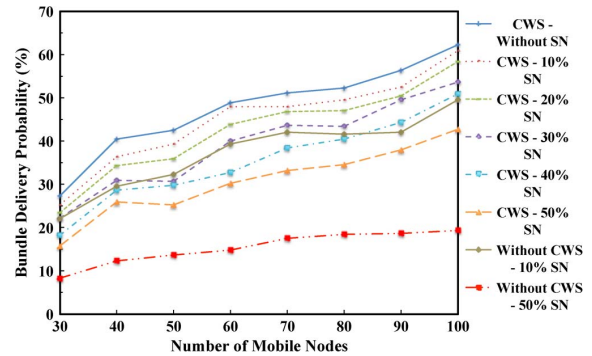


Fig. 4. Bundle delivery probability as function of the number of mobile nodes, considering the binary version of the spray-and-wait routing protocol and a number of selfish nodes changing between 10% and 50%.

B_{ADD} is the bundle average delivery delay, Td_i is the time when the bundle i arrived to its final destination, Tc_i is the time when the bundle i was generated, and NT_{DB} is the total number of unique delivered bundles

$$B_{ADD} = \frac{\sum_{i=1}^{NT_{DB}} (Td_i - Tc_i)}{NT_{DB}}. \quad (8)$$

The overhead ratio measures the bandwidth efficiency of a routing protocol. In other words, it measures the number of “extra” bundles needed for each bundle to be delivered. (9) shows how this metric is calculated, where P_{OR} is the protocol overhead ratio, NT_{RB} is the total number of successfully transmitted bundles, and NT_{DB} is the total number of unique delivered bundles. Finally, the number of dropped bundles is defined as the total number of bundles that have been discarded by nodes from their buffers due to buffer overflow, TTL expiration, or selfish behavior

$$P_{OR} = \frac{NT_{RB} - NT_{DB}}{NT_{DB}}. \quad (9)$$

B. Impact on Bundle Delivery Ratio and Average Delay

To measure the efficiency of the proposed CWS, the observed results of the CWS approach were compared with an approach where no selfish node detection is performed [see Fig. 2(a)–(d)]. This study starts by evaluating the percentage of delivered bundles. As observed in Fig. 4, as the number of selfish nodes increases the bundle deliver probability tends to decrease. However, the CWS manages to reduce the negative impact of selfish nodes. This may be confirmed by comparing the bundle delivery probabilities of CWS with an approach where no action is taken against selfish nodes [see Fig. 2(a)]. Comparing both approaches performing with 10% of nodes behave like selfish nodes (see Fig. 4), the CWS increases the bundle delivery probability in approximately 3%, 7%, 7%, 9%, 6%, 8%, 10%, and 11% (for a number of mobile nodes that are equal to 30, 40, 50, 60, 70, 80, 90, 100, respectively). Furthermore, in the worst evaluated scenario (50% of selfish nodes), CWS contributes to reduce the impact of selfish nodes increasing the bundle delivery probability in approximately 7%,

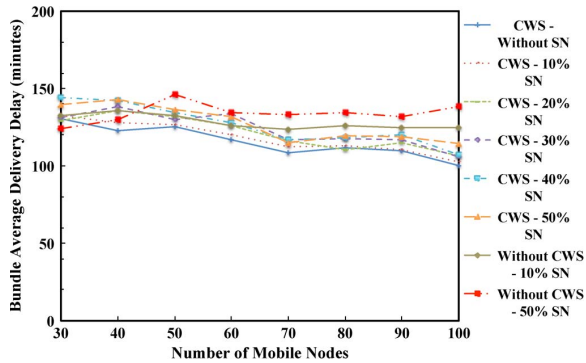


Fig. 5. Bundle average delivery delay as function of the number of mobile nodes, considering the binary version of the spray-and-wait routing protocol and a number of selfish nodes changing between 10% and 50%.

14%, 11%, 15%, 16%, 16%, 19%, and 23%, when compared with an approach where no action is taken against selfish nodes. CWS is not only effective when selfish nodes are detected in the network. In a scenario that only admits cooperative nodes (i.e., nodes that do not diverge from the protocol), the proposed cooperative system also contributes to increasing the bundle delivery probability, when compared with an approach where no incentive is given to this kind of nodes [see Fig. 2(a)]. This happens because CWS rewards nodes for its cooperative behavior, which will make cooperative nodes to share even more resources. Then, the CWS increases the bundle delivery probability in approximately 3%, 4%, 4%, 4%, 5%, 5%, and 5% (for a number of mobile nodes that are equal to 40, 50, 60, 70, 80, 90, 100, respectively).

As it may be observed in Fig. 5, the CWS also achieves better results in terms of the bundle average delivery delay when compared with an approach where no selfish nodes detection is performed [see Fig. 2(b)]. This means that CWS manages to deliver bundles sooner, which is even more pronounced when 50 or more mobile nodes are deployed in the network. For example, if 10% of selfish nodes are considered, the CWS deliver bundles approximately 6, 6, 11, 13, 14, and 22 min sooner (for a number of mobile nodes that are equal to 50, 60, 70, 80, 90, 100, respectively). In addition, for the worst considered scenario (50% of selfish nodes), the CWS manages bundles delivering 9, 3, 19, 15, 13, and 24 min sooner.

The reason behind the observed results for these two metrics is due to the CWS approach in considering nodes reputation score to set the amount of resources that will be shared by them. Allowing contacts only between cooperative nodes will increase nodes reputation score, which will lead to higher percentages of resource sharing. In other words, nodes will share more resources for the benefit of others (e.g., time spent forwarding bundles for others and buffer capacity to store them).

C. Overhead Ratio and Number of Dropped Bundles

Here, the CWS performance is inspected in terms of wasted resources. For this purpose, this evaluation starts by considering

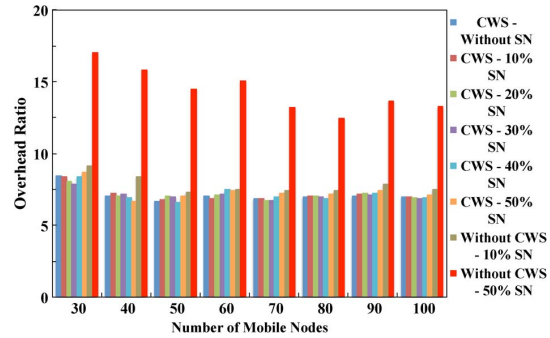


Fig. 6. Overhead ratio as function of the number of mobile nodes, considering the binary version of the spray-and-wait routing protocol and a number of selfish nodes changing between 10% and 50%.

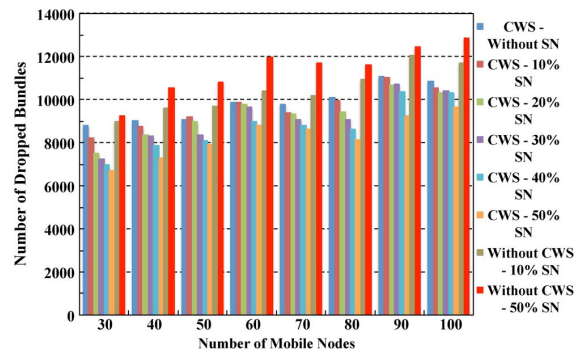


Fig. 7. Number of dropped bundles as function of the number of mobile nodes, considering the binary version of the spray-and-wait routing protocol and a number of selfish nodes changing between 10% and 50%.

the overhead ratio. As shown in Fig. 6, following the CWS approach the overhead ratio does not change significantly, although the increase of the number of selfish nodes. This is a significant achievement if these results are compared with the results observed when no action is taken against selfish nodes [see Fig. 2(c)]. Considering the worst evaluated scenario (50% of selfish nodes), the CWS decreases the overhead ratio in approximately 8, 9, 7, 8, 6, 5, 6, and 6 bundles (for a number of mobile nodes that are equal to 30, 40, 50, 60, 70, 80, 90, 100, respectively).

Regarding the number of dropped bundles (see Fig. 7), the CWS also contributes to decreasing the number of dropped bundles for all the evaluated percentage of selfish nodes. For the 10% approach, the CWS drops less 774, 888, 488, 445, 789, 956, 1019, 1132 bundles when compared with the same approach where no selfish node detection is performed [see Fig. 2(d)]. In the worst studied scenario, the CWS manages to discard less 2566, 3250, 2907, 3140, 3078, 3477, 3210, and 3193 bundles. The CWS manages to decrease the network resource by detecting the presence of selfish nodes and avoiding contacts of this kind of nodes with cooperative nodes. This will save cooperative nodes resources (e.g., buffer space) that will only use them to forward bundles to other cooperative nodes. Avoiding contacts with selfish nodes also ensures that

a higher number of bundles copies travel through the network increasing their possibility to reach the destination node. Otherwise, selfish nodes will delete these copies without being replicated, at least, once.

VI. CONCLUSION AND FUTURE WORK

This paper proposed a CWS for VDTNs to deal with the presence of selfish nodes in the network. This kind of nodes severely affects the overall network performance and may comprise the performance of cooperative nodes since they consume resources from other network nodes to only satisfy their needs. For this paper purposes, a selfish node is defined as a node with a reputation score lower than 20 that drops bundles immediately after receiving them or without sending them, at least, once.

The CWS bases its operation on a cooperative exchange of nodes reputation score and on three modules (classification, neighbor's evaluation, and decision) to detect and exclude selfish nodes from the network. The conducted studies considering the binary version of the Spray-and-Wait routing protocol and the VDTNSim simulation tool prove the effectiveness of this system in attenuate the impact of selfish nodes on the overall network performance. This is achieved by increasing the number of delivered bundles and decreasing the average time they need to travel from the source to the destination node. Furthermore, the CWS scheme also succeeds on the resources waste reduction task by significantly decreases the number of dropped bundles.

For future work, it is intended to take advantages of the CWS to create a cooperative exchange of information (e.g., packet forwarding errors, number of corrupted packets forwarded, nodes energy constraints) that allows the creation of an optimal monitoring and management system to improve the detection of network anomalies.

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Feng Xia (M'07–SM'12) received the B.Sc. and Ph.D. degrees from Zhejiang University, Hangzhou, China.

He was a Research Fellow with Queensland University of Technology, Brisbane, Qld., Australia. He is currently a Full Professor with the School of Software, Dalian University of Technology, Dalian, China.

Dr. Xia is the (Guest) Editor of several international journals. He serves as General Chair, PC Chair, Workshop Chair, Publicity Chair, or PC Member of a number of conferences.



João A. F. F. Dias received the B.Sc. and M.Sc. degrees from the University of Beira Interior, Covilhã, Portugal, in 2009 and 2011, where he is currently working toward the Ph.D. degree under the supervision of Prof. Joel J. P. C. Rodrigues, all in informatics engineering.

He is a Ph.D. student member with the Instituto de Telecomunicações, Portugal. His current research topics include vehicular networks, delay-tolerant networks, and vehicular delay-tolerant networks. He authors or co-authors

21 conference papers, ten International Journal publications, and 2 technical reports.



Joel J. P. C. Rodrigues (S'01–M'06–SM'06) received the Habilitation in computer science and engineering from the University of Haute Alsace, Mulhouse, France, the Ph.D. degree in informatics engineering, and the M.Sc. degree from the University of Beira Interior, Covilhã, Portugal, and a five-year B.Sc. degree (licentiate) in informatics engineering from the University of Coimbra, Coimbra, Portugal.

He is a Professor with the Department of Informatics of the University of Beira Interior and a Senior Researcher with the Instituto de Telecomunicações, Portugal. He is the Leader of NetGNA Research Group (<http://netgna.it.ubi.pt>), the Chair of the IEEE ComSoc Technical Committee on eHealth, the Past-chair of the IEEE ComSoc Technical Committee on Communications Software, Steering Committee member of the IEEE Life Sciences Technical Community, Member Representative of the IEEE Communications Society on the IEEE Biometrics Council. He has authored or coauthored over 400 papers published in refereed international journals and conferences, a book, and 2 patents.

Dr. Rodrigues is the Editor-in-Chief of the *International Journal on E-Health and Medical Communications*, the Editor-in-Chief of *Recent Advances on Communications and Networking Technology*, the Editor-in-Chief of the *Journal of Multimedia Information Systems*, and Editorial Board Member of several international journals.



Constandinos X. Mavromoustakis (S'01–M'06–SM'13) received the five-year dipl.Eng (B.Sc./B.Eng./MEng) degree in electronic and computer engineering from the Technical University of Crete, Chania, Greece, the M.Sc. degree in telecommunications from the University College of London, London, U.K., and the Ph.D. degree from the Department of Informatics, Aristotle University of Thessaloniki, Thessaloniki, Greece.

He is currently an Associate Professor with the Department of Computer Science, University of Nicosia, Egkomi, Cyprus. He is leading the Mobile Systems Laboratory (MOSys Lab., <http://www.mosys.unic.ac.cy/>) in the Department of Computer Science at the University of Nicosia, dealing with design and implementation of hybrid wireless testbed environments, high-performance cloud and mobile cloud computing (MCC) systems, modeling and simulation of mobile computing environments and protocol development and deployment for large-scale heterogeneous networks, as well as new "green" mobility-based protocols.

Dr. Mavromoustakis has been an elected Active Member (Officer/Secretary) of IEEE/R8 regional Cyprus section since February 2014, and since May 2009, he has served as the Chair of the C16 Computer Society Chapter of the Cyprus IEEE section. He is a Management Member of the IEEE Communications Society (ComSoc) Radio Communications Committee (RCC) and served as Track Chair and Cochair of various IEEE International Conferences (including AINA, IWCMC, GlobeCom, IEEE Internet of Things, etc.). He is the recipient of various grants, including the highly competitive European grant of Early Stage Researcher (ESR), for excellent research output and research impact, in December 2013 (EU Secretariat/Brussels).

Chapter 7

Cooperation strategies for Vehicular Delay-Tolerant Networks

This chapter is based on the following paper:

Cooperation strategies for Vehicular Delay-Tolerant Networks

João A. F. F. Dias, Joel J. P. C. Rodrigues, N. Kumar, and K. Saleem

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Cooperation Strategies for Vehicular Delay-Tolerant Networks

João A. F. F. Dias, Joel J. P. C. Rodrigues, Neeraj Kumar, and Kashif Saleem

ABSTRACT

Vehicular communications are emerging as a promising technology to enable communications using vehicles as network nodes. VDTNs appear as a novel approach to enable services and applications where it is not possible to define an end-to-end path. To allow communications in such challenging environments, VDTNs rely for their operation on cooperation between network nodes, which contributes to increasing network connectivity and improving overall network performance. To accomplish such a task, nodes may be asked to share their constrained storage, bandwidth, and energy resources with one another. However, nodes may be unwilling to cooperate in order to save resources or due to selfish behavior. This kind of node severely affects the network functionality. This article gives an overview of the field, providing motivations, challenges, and an evaluation of the impact of cooperative measures on the performance of VDTN networks.

INTRODUCTION

In the last two decades, delay-tolerant networks [1, 2] have been exhaustively studied in order to allow communications in a wide range of extreme scenarios where a conventional end-to-end path may not be available. The vehicular delay-tolerant network (VDTN) [1] has emerged as a new delay-tolerant architecture that aims to provide innovative solutions for challenged vehicular communications. VDTNs exploit opportunistic contacts between vehicles (e.g., cars, buses, trams) and fixed infrastructures to provide connectivity to either urban or remote regions. However, they may also be used for other purposes, such as road safety, driver assistance, or even road traffic optimization.

The VDTN architecture (Fig. 1) follows the Open Systems Interconnection (OSI) reference model and the TCP/IP architecture, which allows the VDTN protocol stack to support services and functionalities performed by the two lower layers. Contrary to other delay-tolerant architectures, VDTNs define an IP over DTN approach by placing a data aggregation and de-aggrega-

tion layer, called a bundle layer, below the network layer. This allows the creation of large-size packets which aggregate IP datagrams that share common characteristics. These large packets are called bundles and define the VDTN protocol data unit. This architecture also gathers contributions from the optical burst switching (OBS) paradigm [3] since it considers an out-of-band signaling approach with separation of the control and data planes. At the control plane, nodes exchange signaling information (i.e., setup messages) using the bundle signaling control (BSC) layer. These messages may be used to make several routing decisions and to set up several parameters of the data plane. For example, according to the information collected at the control plane, nodes may decide to accept/ignore a contact opportunity. The control plane functions are always active, allowing node discovery. At the data plane, bundles are assembled and processed using the bundle aggregation and de-aggregation (BAD) layer. The data plane link is only activated when both nodes in contact are in condition to exchange data bundles. The use of different planes allows nodes to perform independently using their own layers, protocols, and even technologies.

The VDTN architecture considers three different types of nodes: mobile, relay, and terminal nodes. Mobile nodes store-carry-and-forward capabilities are exploited to forward bundles between network nodes (fixed or mobile). Terminal nodes are responsible for generating bundles (traffic sources) and processing incoming bundles from others (traffic sink). They are also responsible for providing connectivity to end users. In several scenarios where it is not possible to have terminal nodes, vehicles may act as terminal nodes. Relay nodes aim to increase the number of contact opportunities, reducing the impact of the high mobility of vehicles that leads to short contact durations. This situation limits the already limited amount of data to be transferred due to bandwidth and transmission ranges [4].

In spite of the improvements already achieved by the VDTN architecture, some of its particular features (e.g., sparse and sporadic contacts between network nodes, huge and inconstant

João A. F. F. Dias and
Joel J. P. C. Rodrigues are
with Instituto de Telecomunicações, University of
Beira Interior.

Joel J. P. C. Rodrigues
is with the University of
Fortaleza.

Neeraj Kumar is with
Thapar University.

Kashif Saleem and Joel J.
P. C. Rodrigues are with
King Saud University.

message delivery delays, frequent network partitioning, and the possible absence of end-to-end connectivity) may compromise overall network performance. Due to these unique features, cooperation between network nodes assumes an important role. It is through this cooperation and their store-carry-and-forward capabilities that bundles travel from a source to their final destination.

This work's main goal is to overview and study the concept of cooperation and how it may influence the performance of VDTNs. The remainder of the article is organized as follows. The next section addresses the cooperation problem and discusses how cooperation functions can be implemented at the control and data planes; then we give an overview of the VDTN cooperation strategies to deal with cooperative/uncooperative nodes. After that, we analyze the impact of cooperative measures on the performance of VDTNs, and the final section concludes the article, providing a summary on cooperation in VDTNs.

COOPERATION IN VEHICULAR DELAY-TOLERANT NETWORKS

In a fully cooperative scenario all network nodes are willing to cooperate. However, in a real scenario this is not a realistic assumption because nodes may reject communications with others in order to save resources or due to selfish/malicious behavior. In fact, one of the major issues faced by vehicular networks is related to resource limitations and their influence on the performance and capacity of the network. To ensure the success of data communications in such networks, it is very important to ensure cooperation between network nodes. Nodes use their resources to perform network functionalities and exchange bundles with each other. In cooperative environments, when a contact opportunity is available, nodes store and forward bundles from others. Such behavior allows DTNs to be resilient to network or individual node failures. Furthermore, when nodes are in a non-cooperative scenario, and no action is performed to motivate them to cooperate, they tend to exhibit selfish behavior. A node with selfish behavior may not be interested in store-and-forward bundles from others. Such behavior can be determined by resource limitations (e.g., storage, energy) or malicious conduct. A network that holds selfish nodes is a network with severely compromised performance.

Following the delay-tolerant paradigm, VDTNs also take advantage of cooperation between network nodes to improve overall network performance. Assuming the separation of the control and data planes, cooperation between network nodes may also be performed separately on these two planes in order to perform all network functions at each contact opportunity (Fig. 2). When network nodes encounter each other, they start to perform control plane functions, which results in the cooperative exchange of crucial information (e.g., location, speed, vehicle destination, energy, and buffer state). Such cooperative exchange allows node discovery and resource reservation to configure the data plane.

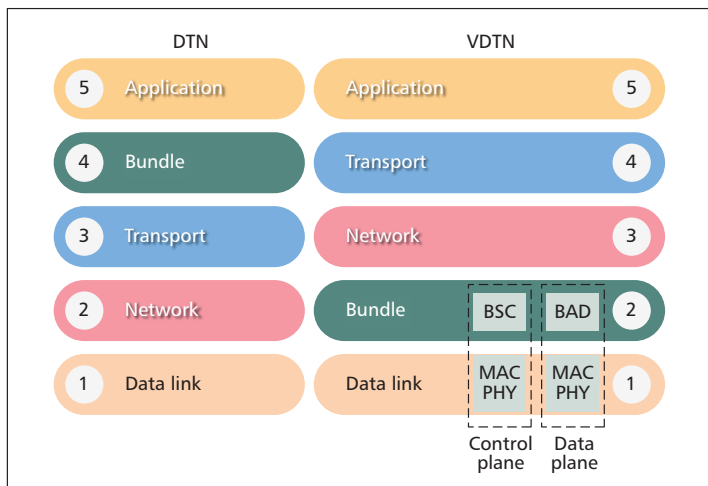


Figure 1. Illustration of the VDTN network architecture in comparison with DTN.

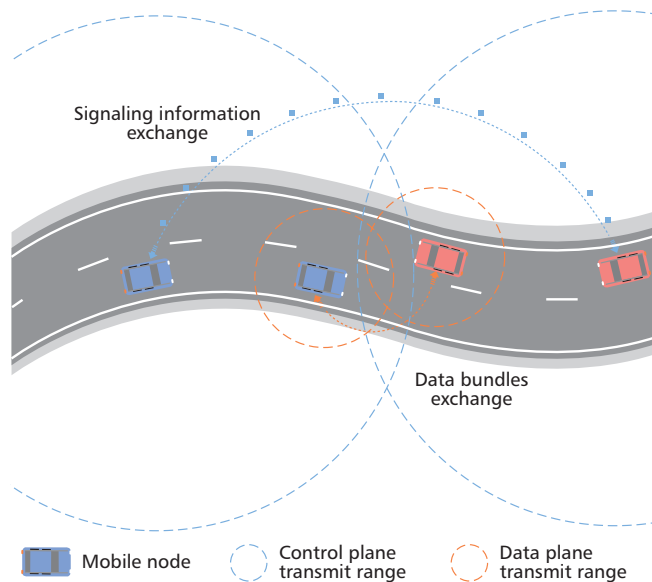


Figure 2. Illustration of the VDTN architecture out-of-band signaling.

For example, sharing geographical information and current speed allows nodes to predict the period of time they will be performing data plane functions or the period of time they will be in range of each other [5]. Afterward, the same information may also be used to configure data plane links to be active only during that period of time and to calculate the maximum number of bytes that can be transferred avoiding bundle fragmentation. Such an approach has a huge impact on power savings, which is very important in a network with energy constraints. The information cooperatively exchanged at the control plane also allows nodes to decide if a contact opportunity is suitable to accept or ignore. In other words, a node might decide to ignore a contact opportunity if the other one presents

To improve cooperation between network nodes, other information can also be exchanged, such as bundle delivery notifications, routing state information, or even nodes' reputation scores. This can be a starting point to propose cooperative mechanisms and reputation systems that optimize network nodes' performance.

energy or buffer space constraints. This approach prevents bundle dropping after a transmission process, which results in unnecessary energy consumption. To improve network performance, other kinds of information can be cooperatively exchanged at the control plane.

At the data plane, network nodes must cooperate in order to forward data bundles between source and destination. However, it is not possible to take for granted fully cooperative behavior, since nodes, in spite of their cooperative behavior, may prefer to schedule their own bundles first. Nodes may also be unwilling to unconditionally store all bundles sent by others in order to save buffer resources or maintain data integrity. Both situations may limit network performance.

To improve cooperation between network nodes, other information can also be exchanged, such as bundle delivery notifications, routing state information, or even nodes' reputation scores. This can be a starting point to propose cooperative mechanisms and reputation systems that optimize network nodes' performance.

COOPERATION STRATEGIES FOR VEHICULAR DELAY-TOLERANT NETWORKS

As described above, VDTN operations depend on how nodes cooperate with each other. This dependence may raise many challenges if nodes diverge from the protocol for a given reason. The presence of non-cooperative nodes in VDTNs leads to degradation of the performance of the entire network. In the literature, there are several studies [6–8] that deal with this problem. Nevertheless, they cannot be directly applied to VDTNs. This section summarizes the advances already achieved on cooperation for VDTNs. It starts with the presentation of a reputation system that considers several incentive mechanisms, which reward or punish nodes for their cooperative behavior. Thus, a cooperative watchdog developed for VDTNs is presented and described in detail.

REPUTATION SYSTEM

When it is not possible to create a fully cooperative scenario, it is important to afford the network strategies to deal with non-cooperative nodes. The VDTN reputation system [9] is a tool that is able to identify non-cooperative nodes by performing two distinctive steps (Fig. 3):

- Isolate and avoid contact with non-cooperative nodes.
- Monitor and motivate these nodes to cooperate.

To allow the reputation system operation, each node builds a reputation table containing all encountered nodes and their reputation score. Each time a contact opportunity is available, nodes exchange signaling information (e.g., location, destination, current speed) and statistics (e.g., energy or buffer status, reputation score). This signaling information is exchanged using the control plane at the connection setup phase. If nodes' reputation scores have changed since

the last meeting, both scores are updated in the nodes reputation table.

After exchanging and processing the control information, the reputation system will perform its operation based on the chosen mode. If the reputation system is set up to isolate and exclude non-cooperative nodes from the network (mode 1), the reputation score of nodes is used to decide whether to accept or reject a contact opportunity. If the reputation score is higher than the network reputation threshold (Δ), the contact is accepted and nodes are able to forward bundles between each other, performing all data plane functionalities. At the end of data plane operations, nodes' reputation scores are recalculated taking into account their performance during the contact opportunity. In the second mode, the reputation system also classifies network nodes according to their reputation scores. However, contrary to the first mode, in this mode, misbehaving nodes start to be monitored for a predefined period of time (C_i). During this period, a monitored node is encouraged to share its own resources in order to continue consuming network resources. After the monitoring time, if it stills exhibiting non-cooperative behavior, it is excluded from the network. On the other hand, if the node starts sharing its own resources, it is rewarded by the reputation system with an increase of its reputation score to a value equal to the network cooperative threshold, and it is marked as a partially cooperative node. Being a partially cooperative node means that the reputation system will continue monitoring this node in order to verify that it continues to share its own resources. The reputation system workflow considering the two performing modes is illustrated in Fig. 3.

The reputation system considers several incentive strategies [9] to update the reputation score of each node. All strategies base their performance on two metrics: the number of deliveries and the number of dropped bundles. The reputation score of a node increases each time it successfully delivers a bundle to its final destination. On the other hand, when a node drops a bundle without exchanging it at least once, its reputation score decreases. *Simple increment simple decrement* (SISD), *double increment simple decrement* (DISD), and *simple increment double decrement* (SIDD) heuristics [9] share the same reasons to reward/punish nodes. The main difference between these schemes is how many nodes are rewarded/punished. The DISD scheme distinguishes itself from the SISD scheme by increasing nodes' reputation score by $2k$ units. The SIDD differs from the SISD scheme by punishing nodes in $2k$ units each time a bundle is dropped without having sent at least once. The *simple increment message hop decrement* (SIMHD) scheme [9] takes into account a bundle's path (i.e., hops between source and current node) to punish nodes when they drop a bundle without sending it at least once. This approach manages to punish selfish nodes in a more aggressive way than the previous schemes. A node's reputation score decreases $2k + h*k$ units each time a bundle is dropped without being sent at least once. In this equation, h represents the number of bundle hops until the current node. This scheme intends to punish mis-

behaving nodes taking into account other nodes' efforts in forwarding bundles.

Conducted studies considering all four schemes [9] show that schemes that punish selfish nodes in a more aggressive way (SIMHD and SIDD) contribute to increasing overall network performance. This happens since such schemes manage to detect and avoid contacts with selfish nodes sooner.

COOPERATIVE WATCHDOG SYSTEM

The cooperative watchdog system (CWS) [10] aims to afford nodes with the capability to detect non-cooperative nodes without need for a centralized system. To perform such a task, each network node has a reputation score (α) which is used to determine the percentage of resources that may be shared with others. At the beginning of network operations all network nodes have a reputation score equal to 50, and over time it may change between 0 and 100. Nodes' reputation scores are updated and spread through the network, taking advantage of VDTN out-of-band signaling. While performing the control plane, nodes share information (e.g., number of relayed, dropped, and delivered bundles) about their performance in previous contact opportunities. This exchange allows nodes to evaluate each other, which will be stored in a neighbor reputation table that all network nodes maintain. The same information is also collected by the CWS in order to keep a record of the performance of each node in the network.

At the end of the data plane, the system updates the reputation score of all nodes that participated in the contact opportunity, taking into account three different kinds of scores: a node reputation score observed by its neighbors, a cooperative value assigned by the watchdog, and a node reputation score observed by the node itself [10]. Each of these scores is calculated independently using a different module. The neighbor's evaluation module aims to collect a node's neighbors' opinions. To perform this task, at the end of each contact opportunity, this module sends a request to N neighbors of a node asking them to share their opinion about their neighbor. When all the neighbors' answers are collected, the average of these scores is calculated, resulting in the node reputation score observed by its neighbors. To assign the cooperative value of a node, the CWS considers the impact of a node on the network. To calculate this impact, the number of relayed, delivered, and dropped bundles (information exchanged at the control plane) is considered. A node that has a normalized ratio between the number of delivered and dropped bundles closer to one is a cooperative node that contributes to increasing the overall performance of the network. For this reason, the CWS classifies this node as a cooperative node. On the other hand, a node that has the same ratio closer to zero is a possible non-cooperative node and is classified as a misbehaving node.

Finally, the decision module uses an interface that communicates with the reputation system [9] which is deployed locally in each node. This approach aims to give nodes the ability to generate an opinion on their own performance. Having collected this score, the decision module calcu-

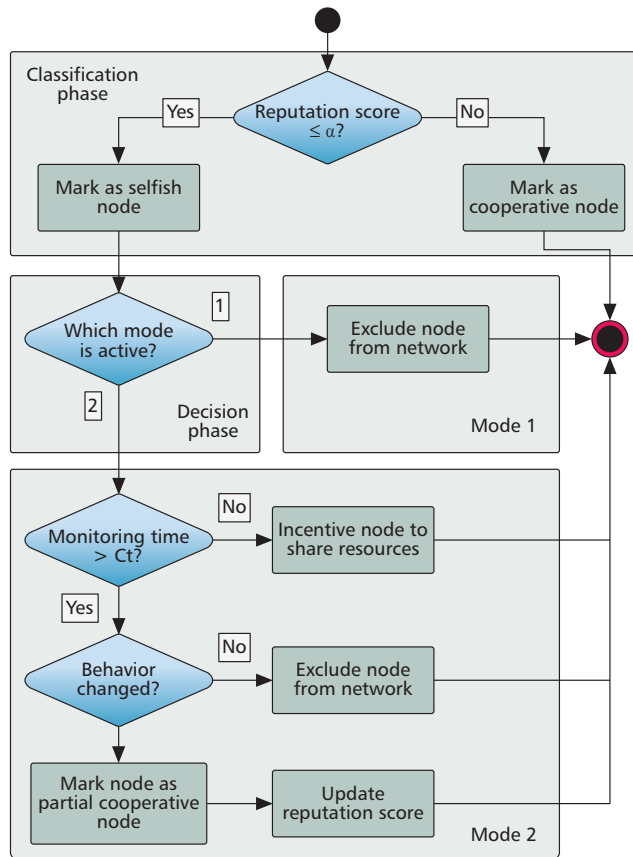


Figure 3. Illustration of the reputation system workflow deployed in VDTNs.

lates the new node reputation score based on all the scores calculated by the other modules and the importance imputed to each score. If the CWS is programmed to give more importance to the node opinion about itself, the score collected by the decision module will have a greater weight on the final equation. For example, if the system gives the node opinion a weight of 60 percent in the equation, 60 percent of the new reputation score will be given by the score calculated by the node itself and 40 percent will be given by the neighbors' score. The cooperative value assigned by the CWS will be used to reward or punish nodes for their cooperative behavior. A node's reputation score dropping below 20 causes the system to generate an alarm that will be spread by the network, informing all nodes to avoid contact with this specific node.

PERFORMANCE EVALUATION OF COOPERATIVE STRATEGIES ON VDTNs

In this section the impact of the above cooperation strategies on the performance of VDTNs are compared and analyzed. To perform this task, a simulation scenario was created in the

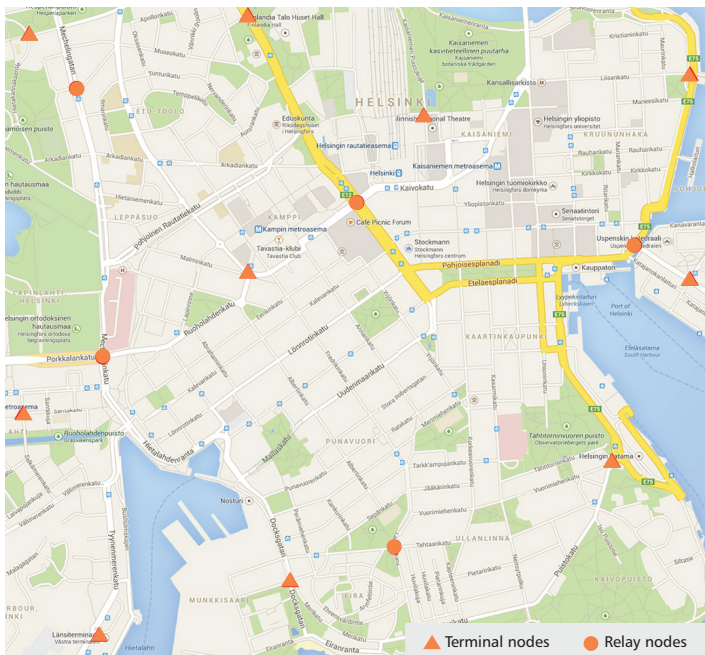


Figure 4. Simulation scenario representing a part of Helsinki, Finland, and the location of terminal and relay nodes.

VDTN simulator (VDTNsim) [11], representing a part of the city of Helsinki, Finland (Fig. 4). This tool was used because it was developed to emulate the most important principles of the VDTN architecture. In this section, the considered scenario is described, and a detailed analysis of the conducted performance studies is presented focusing on the impact of the above two strategies on the overall network performance when non-cooperative nodes are present in the network.

NETWORK SCENARIO

Considering the scenario illustrated in Fig. 4 and a simulation period of 24 h, five relay nodes (each one with 200 MB of buffer capacity) were placed at the most important intersections. Ten terminal nodes (each one with 100 MB of buffer capacity) act as traffic source and traffic sinks. The number of mobile nodes (including cooperative and non-cooperative nodes) changes in the range of [30, 100]. All mobile nodes move along map roads with an average speed of 50 km/h and are equipped with a buffer with 50 MB capacity. To perform the out-of-band signaling, all network nodes are equipped with omnidirectional antennas, allowing a transmission range of 30 m and a transmission data rate of 6 Mb/s.

Bundles are uniformly generated in the range of [25, 35] s with a size uniformly distributed in the range of [50 kB, 750 kB]. Bundles have 360 min of time to live (TTL) to reach their final destination (i.e., another terminal node selected at creation time) or they will be dropped. Bundles may also be dropped due to buffer congestion. The binary version of the Spray and Wait routing protocol [12] (assuming eight bundle copies) was chosen as the underlying routing scheme.

To measure and evaluate the strategy's performance, the number of unique bundles that have been successfully delivered to destination nodes (bundle delivery probability) and the protocol overhead ratio were considered.

This network setup is intended to measure the efficiency of the two proposed mechanisms when deployed in an urban scenario with different levels of traffic (30 to 100 mobile nodes moving at an average speed of 50 km/h), to evaluate how both systems deal with bundle storage and TTL constraints (mobile nodes have a buffer capacity of 50 MB and have to deliver bundles in less than 360 min), and also to demonstrate the importance of the approach introduced by both of the systems in dealing with the presence of selfish nodes in the network.

IMPACT ON BUNDLE DELIVERY RATIO

To analyze the performance of the two strategies, this study starts with analysis of the bundle delivery ratio. To do this, the percentage of non-cooperative nodes changes between 10 and 50 across all the experiments (30 for each point). This kind of node is discarded from the network when its reputation score is below the network reputation threshold (Δ), which was set to 20 at the beginning of network operations. As may be observed in Fig. 5, both strategies contribute to increase the number of unique delivered bundles when compared to an approach where no action is taken against non-cooperative nodes. Performing an analysis of the same figure allows one to conclude that the reputation system outperforms the CWS. This can be confirmed by comparing the two approaches performing with the same percentage of non-cooperative nodes. For example, when 50 percent of the mobile nodes are non-cooperative, the reputation system manages to increase the bundle delivery probability in approximately 5, 4, 6, 3, 3, 5, 3, and 2 percent (for a number of mobile nodes equals to 30, 40, 50, 60, 70, 80, 90, and 100, respectively). The reason this happens is because the reputation system manages to detect non-cooperative nodes more quickly, limiting their negative impact on the network. This particular feature is very important in scenarios with low node density. In such scenarios forwarding a bundle to a non-cooperative node could mean that this bundle may be dropped without a sufficient number of copies in the network to reach its final destination.

IMPACT ON PROTOCOL OVERHEAD

The protocol overhead ratio represents how many "extra" copies of a bundle are needed to deliver it to its final destination. As may be seen in Fig. 6, both approaches manage to decrease the amount of "extra" bundles when compared to the approach where no action is taken against misbehaving nodes. This is achieved by avoiding contact with such nodes, ensuring that bundle copies are transmitted only to nodes that are willing to forward them to others or to their final destination. This approach also decreases nodes' resource consumption since fewer transmissions are needed to deliver bundles to their final destination. Although both strategies contribute to decrease the protocol overhead ratio, the reputation system achieves better results. For example,

considering the worst evaluate scenario (50 percent of non-cooperative nodes), the reputation system decreases the protocol overhead ratio in 2, 1, 3, 2, 2, 2, 2, and 3 bundles compared to the CWS. This happens due to the fact that the reputation system manages to decrease the number of bundle copies that are forwarded to misbehaving nodes, reducing the effort that cooperative nodes have to make to deliver bundles to their final destination (e.g., storing and sending more bundle copies). This situation also allows bundles to reach their final destination sooner.

CONCLUSION

This article is focused on cooperation among nodes in VDTNs, especially on how this architecture deals with the presence of misbehaving nodes. Allowing misbehaving nodes in the network contributes to a huge decrease of network efficiency. To deal with these nodes, two strategies are presented, and their performance compared and analyzed. Both approaches try to balance the amount of resources shared with other nodes in order to not compromise nodes' integrity. The reputation system considers different incentive mechanisms to calculate nodes' reputation scores. Nodes' reputation scores are compared to the network reputation threshold (α) in order to classify nodes as cooperative or non-cooperative. Then the reputation system may decide whether to exclude or monitor non-cooperative nodes. The cooperative watchdog follows a similar approach, but contrary to the reputation system, which considers incentive mechanisms, it bases its operation on cooperative exchange of nodes' performance metrics and neighbor evaluation to classify nodes.

Conducted studies have shown the effectiveness of both approaches in improving the network performance when non-cooperative nodes are allowed in the network. They not only increase the probability of bundles reaching their final destination, but also manage to decrease the amount of wasted resources, resulting in power and energy savings, which is very important in networks with resource constraints like VDTNs.

For future research work, in order to obtain network performance improvements, several monitoring and management schemes may be developed.

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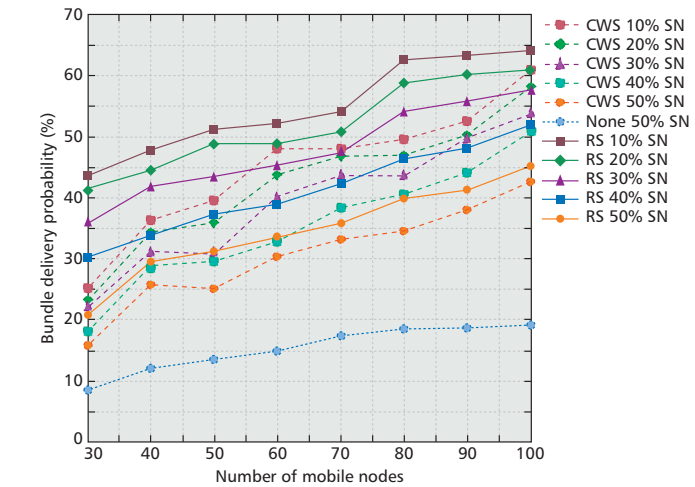


Figure 5. Bundle delivery probability as function of number of vehicles, from 30 to 100, considering the two strategies to deal with non-cooperative nodes in VDTN networks.

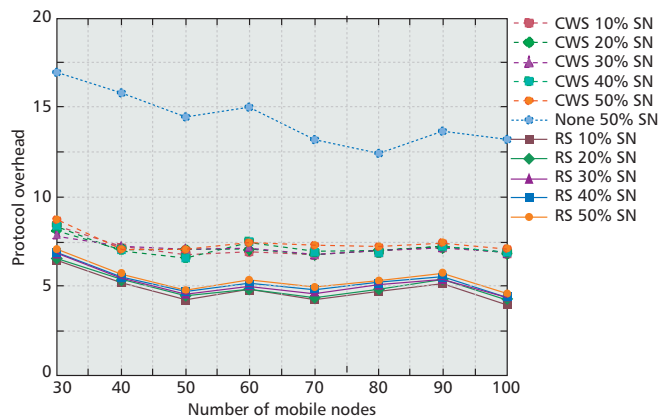


Figure 6. Protocol overhead as function of number of vehicles, from 30 to 100, considering the two strategies to deal with non-cooperative nodes in VDTN networks.

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BIOGRAPHIES

JOÃO A. F. F. DIAS received a B.Sc. degree in informatics engineering from the University of Beira Interior, Portugal, in 2009. In 2011 he received his M.Sc. degree in informatics engineering from University of Beira Interior. Currently, he is a Ph.D. student in informatics engineering at the University of Beira Interior under the supervision of Prof. Joel J. P. C. Rodrigues. He is also a Ph.D. student member of the Instituto de Telecomunicações, Portugal. His current research topics include vehicular networks, delay-tolerant networks, and vehicular delay-tolerant networks. He has been an author or co-author of 21 conference papers, 10 international journal publications, and 2 technical reports.

JOEL J.P.C. RODRIGUES (joeljrc@ieee.org) [S'01, M'06, SM'06] is a professor in the Department of Informatics of the University of Beira Interior, Covilhã, Portugal, and a senior researcher at the Instituto de Telecomunicações, Portugal. He received the Academic Title of Aggregated Professor from the University of Beira Interior, the Habilitation in computer science and engineering from the University of Haute Alsace, France, a Ph.D. degree in informatics engineering and an M.Sc. degree from the University of Beira Interior, and a five-year B.Sc. degree (licentiate) in informatics engineering from the University of Coimbra, Portugal. He is the leader of the NetGNA Research Group (<http://netgna.it.ubi.pt>), President of the scientific council at ParkUrbis Covilhã Science and Technology Park, Chair of the IEEE ComSoc Technical Committee on eHealth, Past Chair of the IEEE ComSoc Technical Committee on Communications

Software, a Steering Committee member of the IEEE Life Sciences Technical Community, a Member Representative of the IEEE Communications Society on the IEEE Biometrics Council, and an officer of the IEEE 1907.1 standard. He is Editor-in-Chief of the *International Journal on E-Health and Medical Communications*, Editor-in-Chief of *Recent Advances on Communications and Networking Technology*, Editor-in-Chief of the *Journal of Multimedia Information Systems*, and an Editorial Board member of several journals. He has been General Chair and TPC Chair of many international conferences, including IEEE ICC, IEEE GLOBECOM, and HEALTHCOM. He is a member of many international TPCs and has participated in several international conferences' organization. He has authored or coauthored over 450 papers in refereed international journals and conferences, a book, and 2 patents. He had been awarded several Outstanding Leadership and Outstanding Service Awards by IEEE Communications Society and several best paper awards. He is a licensed professional engineer (as a Senior Member), a member of the Internet Society, an IARIA fellow, and a Senior Member ACM.

NEERAJ KUMAR received his Ph.D. in computer science engineering from Shri Mata Vaishno Devi University, Katra, India, and was a postdoctoral research fellow at Coventry University, United Kingdom. He is an associate professor in the Department of Computer Science and Engineering, Thapar University, Patiala, India. He has published more than 100 scholarly research papers in leading journals and conferences of IEEE, Elsevier, Springer, Wiley, and so on. Some of his research findings are published in top-cited journals such as *IEEE Transactions on Industrial Electronics*, *IEEE Transactions on Dependable and Secure Computing*, *IEEE Transactions on Intelligent Transportation Systems*, *IEEE Transactions on Consumer Electronics*, *IEEE Network*, *IEEE Communications Magazine*, *IEEE Wireless Communications*, *IEEE Internet of Things Journal*, *IEEE Systems Journal*, *Future Generation Computer Systems*, *Journal of Network and Computer Applications*, and *Computer Communications*. He has guided many research scholars to Ph.D. and M.E./M.Tech. degrees. His research is supported by funding from TCS and UGC.

KASHIF SALEEM is currently working as an assistant professor at the Center of Excellence in Information Assurance (CoEIA), King Saud University, Kingdom of Saudi Arabia. He received his Ph.D. (electrical engineering) and M.E. (electrical engineering — electronics & telecommunication) from Universiti Teknologi Malaysia in 2007 and 2011, respectively. His research interests include ubiquitous computing, biologically inspired algorithms, the Internet of Things, machine-to-machine communications, wireless mobile networks, wireless sensor networks, and mobile ad hoc networks. He has authored several research publications and handles ICT related funded research projects in the Middle East and European Union.

Chapter 8

Network Management and Monitoring Solutions on Vehicular Communications: A Survey

This chapter is based on the following paper:

Network Management and Monitoring Solutions on Vehicular Communications: A Survey

João A. F. F. Dias, Joel J. P. C. Rodrigues, Kashif Saleem, Neeraj Kumar, Mario L. Proença Jr.

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Network Management and Monitoring Solutions on Vehicular Communications: A Survey

João A. F. F. Dias¹, Joel J. P. C. Rodrigues^{1,2,3,4}, Kashif Saleem⁵, Neeraj Kumar⁶, Mario L. Proença Jr.⁷

¹*Instituto de Telecomunicações, Universidade da Beira Interior, Covilhã, Portugal*

²*National Institute of Telecommunications (Inatel), Santa Rita do Sapucaí-MG, Brazil*

³*ITMO University, St. Petersburg, Russia*

⁴*University of Fortaleza (UNIFOR), Fortaleza-MG, Brazil*

⁵*Center of Excellence in Information Assurance (CoEIA), King Saud University, Riyadh, Saudi Arabia*

⁶*Department of Computer Science and Engineering, Thapar University, Patiala (Punjab), India*

⁷*State University of Londrina, Londrina, Brazil*

joao.dias@it.ubi.pt, joeljrc@ieee.org, ksaleem@ksu.edu.sa, neeraj.kumar@thapar.edu, proenca@uel.br

Abstract— Vehicular communications are emerging as a promising technology to enable reliable and low-cost solutions for Intelligent Transport Systems (ITS) due to their huge potential to be considered for multiple purposes and scenarios. These networks are characterized by unique and challenging features like packet fragmentation, low node density, short contacts duration, and network disruption. These features may lead to the possible non-existence of a path between the source and destination node, which is one of the most challenging issues faced by this kind of networks. In order to overcome some of them, it is necessary to afford vehicular networks with sophisticated monitoring and management solutions. However, designing and proposing efficient solutions is not an easy task, since this topic is one of the most challenging in terms of research due to their particular characteristics. This paper elaborates on a comprehensive survey focusing on the promising proposals to deal with monitoring and management functionalities in vehicular networks. This work aims not only presenting the state of the art on monitoring and management solutions but also analyzing their benefits and drawbacks, identifying open issues, and providing guidelines for further contributions.

Index Terms— Delay-Tolerant Network, Intelligent Transport Systems, Monitoring, Network Management, Vehicular Ad Hoc Network, Vehicular Communications, Vehicular Delay-Tolerant Network

I. INTRODUCTION

Vehicular architectures [1-3] are emerging as a promising alternative to the conventional Internet allowing to implement low-cost infrastructures to enable the deployment of services and applications, especially where a network infrastructure is not available [4]. To deal with the lack of a network infrastructure, vehicular networks exploit vehicles, with wireless communication devices, to create a temporary self-organized network [5]. Following this approach, such networks can provide communications support for multiple environments (e.g., urban, remote/rural, and catastrophic) [6-8]. For example, several road traffic optimization and road safety applications [9-13] were proposed to provide driving

assistance. Although their applicability, the absence of an end-to-end path in vehicular networks raises several issues that must be overcome [14]. Sporadic contact opportunities between network nodes, long and variable messages delivery delay, and high error rates are examples of these issues. In order to deal and solve some of these issues several vehicular architectures were proposed [15].

Vehicular Ad Hoc Networks (VANETs) [16, 17] exploit vehicles as mobile nodes, exposing them to traffic conditions and regulations. In this kind of networks, vehicles may interact with other vehicles or with roadside infrastructures. Following this approach, most of the proposals for VANETs consider three different types of network infrastructure to enable communications between vehicles [18-20]: (i) an ad hoc infrastructure where vehicles communicate with other vehicles (V2V); (ii) an infrastructure with several roadside units with wireless capabilities that may communicate with vehicles (V2I), (iii) an infrastructure that combines the previous ones. Common to all these approaches is the assumption of an end-to-end connectivity, which makes the VANET architecture susceptible to frequent disconnection, network fragmentation, and longtime delays.

The Delay-Tolerant Network (DTN) architecture [21-24] supports intermittent communications between network nodes. This architecture overlays the bundle layer placing it under the application layer, allowing to implement a store-carry-and-forward paradigm that exploits the high mobility of mobile nodes to enable communications between nodes, building a hop-by-hop session for data transfer. Following a DTN approach and gathering contributions from other technologies, Vehicular Delay-Tolerant Networks (VDTN) [25, 26] propose a network architecture where the communication is divided into two phases (i.e., control and data planes) allowing to implement an out-of-band signaling strategy. Contrary to DTNs, VDTNs places the bundle layer beneath the network layer, which is responsible to aggregate incoming IP data packets into bundle messages, allowing to forward larger

packets (called bundles) instead of small IP (Internet Protocol) datagrams. This architecture supports three distinct types of nodes: terminal, relay, and mobile nodes. Terminal nodes are responsible to generate and receive data. Relay nodes are usually placed at crossroads and have a large storage capability, which allows them to store a huge amount of data that will be forwarded to mobile nodes when a contact opportunity is available. These devices also aim to increase the number of contact opportunities, which will result in a higher data delivery rate [27]. Finally, mobile nodes are exploited to collect, store, and deliver data to its final destination. Mobile nodes can also act as terminal nodes when they generate or are the final destination of data.

Although all the achievements and issues solved by the above-presented architectures, there are some key issues that must be solved in order to increase the confidence on the use of vehicular communications. For example, in such challenging environments the network must be capable to deal with traffic constraints, constant topology changes due to the high mobility of nodes, frequent communication and data losses, and limited network resources. It is expected, that by performing network management and monitoring operations and mechanisms (e.g., routing optimization algorithms, handoff methodologies, resources constraints detection) some of these issues and constraints can be overcome [28]. Usually, network management operations are ensured by routing protocols, since they have the sole purpose to route packets in the best interests of the network. However, external solutions are needed to optimize parameters of routing protocols. Such approach may lead to more stable topologies and lower control traffic overhead, increasing the delivery ratio, decreasing the end-to-end delay, and the resource consumption (e.g., bandwidth and energy). Different kind of solutions for management purposes were proposed for wireless networks [29-32], however due to the single characteristics of vehicular networks, they cannot be directly applied. Some of them may be adapted to work in vehicular environments, nevertheless new mechanisms must be proposed.

To promote further investigations, this paper analyzes and discusses the most relevant research efforts related to management and monitoring techniques for ad hoc and vehicular communications, focusing on how the proposed solutions are designed or adapted to be deployed in vehicular networks. It began with an overview on mobility management approaches, which deal and try to solve several issues regarding the high mobility of mobile nodes and the highly dynamic network topology. Both problems are emphasized by mobile nodes density and network flows. To deal with these problems and improve the network performance, traffic management methodologies are considered. Moreover, the possible non-existence of a direct path between messages source and destination introduces in vehicular communications, several concerns regarding latency, data integrity, and resource consumption. Techniques to solve these concerns are studied and discussed in detail. Lastly, a discussion and open issues on network management practices for vehicular environments are identified.

Thus, the main contributions of this paper are the following:

- Identification and description of the most relevant challenges and constraints regarding network monitoring and management in vehicular communications;
- A detailed review of the state of the art considering the most relevant contributions to perform monitoring and management functionalities in wireless and vehicular environments;
- A discussion on network management and monitoring techniques for vehicular networks, and the identification of open issues for further research works.

The remainder of this survey is organized into five sections. Section II describes the challenges and the most relevant activities that can be considered to deal with management and monitoring purposes in vehicular networks. Section III details on mobility management and how these approaches can be deployed in vehicular communications. Section IV summarizes the most important contributions related to traffic management and monitoring, enumerating the most important works for this kind of solutions. Section V overviews the state-of-the-art on communications, services, data, and resource management strategies, while the last Section presents the main conclusions withdrawn from this study and points several research topics that may be addressed as future work.

II. CHALLENGES TO PERFORM MANAGEMENT/MONITORING ACTIVITIES IN VEHICULAR NETWORKS

Network management and monitoring functionalities allow to take care of disparate networks, handling the exchange of thousands of messages coming from multiple devices and changes in communication requirements and architecture. Contrary to the traditional Internet, performing both functionalities in vehicular environments is not an easy task. Unique characteristics (e.g., possible absence of an end-to-end path, intermittent connectivity, dynamic topology, nodes mobility and density) from such architectures raise several challenges that must be considered to propose efficient management and monitoring approaches.

This section overviews the most relevant challenges raised by vehicular networks that may have significant impact on management and monitoring activities.

A. Dynamic Ad Hoc Topology and Nodes Mobility

The highly dynamic network topology instigated by mobile nodes density and mobility is one of the most challenging issues that vehicular architectures must overcome. As the network topology constantly changes over time, no a priori topology planning is possible for a network administrator. Therefore, new nodes may join or exit the network at any moment, changing not only the network topology but also node density, which can rise several problems regarding routes discovery, leading to suboptimal routes and structures. Such situation ends on a huge waste of resources. A possible solution to reduce the impact of the highly dynamic topology

and minimize the effects of such issue and enable high-speed and seamless services for vehicular networks [33] is to propose mobility management methodologies (described and analyzed in Section III) that deal with network routes and structure updates aiming to reflect the current state of the network topology [34]. However, mobility protocols present performance limitations (e.g., latency) in highly dynamic scenarios and the proposal of inefficient methodologies may result not only in a large amount of resources wasted but also in suboptimal routes [35].

The above-presented problem is strengthening by mobile nodes movement, which is influenced by traffic rules and road conditions (e.g., congestion, traffic lights and rules, pedestrians). This situation may lead to huge delays while travelling, which have a negative impact not only on the performance of mobile nodes but also on the overall network. For example, traffic congestion may lead to an increase of energy consumption and message delivery delay. To overcome this issue, efficient traffic and routing management and monitoring strategies should be proposed (as described in Section IV). These strategies may consider traffic prediction mechanisms aiming to avoid road congestion or routes optimization algorithms capable to choose the best paths to deliver a message to its final destination.

B. Bandwidth and Resources Limitations

Due to the velocity of mobile nodes and the nature of wireless channels, communication bandwidth may be far lower in vehicular environments. In the opposite way, packet loss rates tend to be higher when compared to the traditional Internet. To increase this problem vehicular networks are also characterized by short contacts durations, which limits the volume of data that can be transferred at each contact opportunity, presenting huge limitations for the proposal of multimedia sharing applications.

Limited network resources can further exacerbate this situation, since the lack of resources may force nodes to avoid following protocol to prevent their data from being compromised. In order to facilitate and instigate the development of new applications and services, several management approaches to deal with communications, data, and resource management should be employed in vehicular environments (as described in Section V). For example, some approaches to monitor network conditions can be proposed providing complete reports and statistics to network administrators, helping them to create measures to increase the overall network performance. Moreover, this may allow investigating performance issues, such as unnecessary network bandwidth consumption.

III. MOBILITY MANAGEMENT

Network mobility management operations are responsible for managing and maintaining Internet connectivity between groups of mobile nodes, aiming to achieve an optimal network performance. Mobility management proposals for vehicular networks should be designed taking into consideration the

specific requirements of vehicular environments: communications between vehicles (V2V) and between vehicles and some kind of roadside infrastructure (V2I). Based on these two types of communications, a taxonomy for mobility approaches in vehicular networks can be defined (Fig.1). In V2V communications, most of the mobility management schemes focus on route discovery and maintenance [34] aiming to deal with high dynamic topologies, location, and handoff issues. On the other hand, schemes to deal with mobility in V2I communications are proposed to deal with host and network issues, such as route optimization and integration with VANETs. Most of them consider some Internet mobility management protocols (e.g., Mobile IPv4 [36] and Mobile IPv6 [37]). However, the common implementation of these protocols introduces high handover latency and increases the amount of data loss, as shown in [38].

The most relevant proposals and approaches for monitoring and management functionalities are presented and discussed through this section, as well as the major open issues that will allow to propose new approaches to overcome some of them.

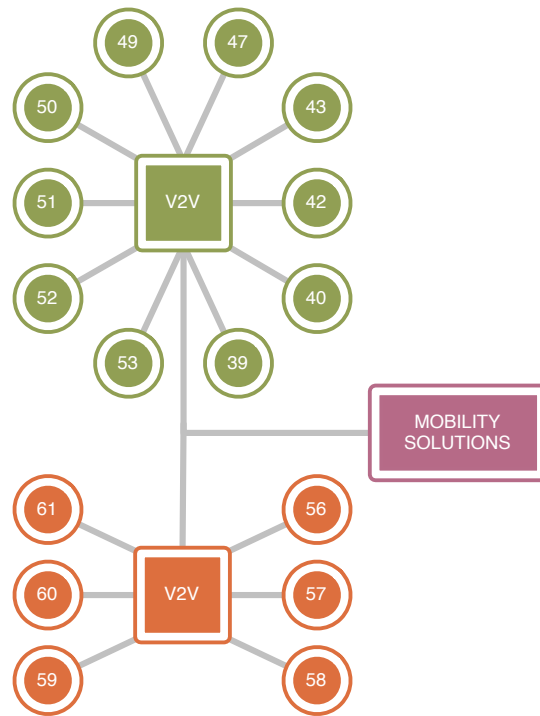


Fig. 1. Taxonomy of mobility solutions to perform management and monitoring functions on vehicular networks considering the two types of communications between nodes (V2V and V2I).

A. Mobility Mechanisms for V2V Communications

Communications between vehicles (V2V) raise several issues (e.g., movement detection or handoff decision) that must be overcome in order to increase the reliability of vehicular networks. Different protocols, schemes, and approaches may be considered. Network Mobility (NEMO)

for network mobility support (NBS) [39] was proposed to allow MIPv6 to manage a set of moving nodes in order to provide a continuous network connection. To accomplish such task, individual mobile nodes have their own Home Agent (HA) that controls all data forwarded between nodes. Although the improvements achieved by this approach, a triangle routing problem may comprise its performance since the HA controls the path between the correspondent and mobile nodes, establishing the third vertex of the communication triangle. To deal with this problem, MIRON [40, 41], NERON [42], and SINEMO [43] were proposed. In order to deploy NEMO in vehicular networks several approaches, schemes, and applications were proposed [44-49]. From these proposals, there are two that stand out. In [47], authors proposed a novel mobility management scheme that divides vehicles into different clusters based on geographical distance and related velocity. This approach aims to create different mobile networks where ad hoc intra-communications are instigated by routing protocols allowing to decrease not only the handoff latency but also the number of lost packets. Following a similar approach, the work presented in [49] proposes a fast handoff scheme that uses assistance nodes to deliver new care addresses to mobile routers helping them to scan network channels and reducing the network handoff latency. Simulation results shown that this scheme manages to reduce handoff latency maintaining the packet interval.

Optimized NEMO (ONEMO) [50] was proposed as a route optimization method that offers a different path than the default bi-directional tunnel maintained by NBS. This is achieved by transferring the responsibilities of the HA to the corresponding router (CR). This task is accomplished by implementing a discovering scheme at mobile routers aiming to find its CR. This scheme sends a discovery request to all addresses derived from the corresponding network node prefix. When a bi-directional tunnel is established, the entire traffic from the network starts to be controlled by the HA. Conducted studies shown that ONEMO manages to decrease the packet overhead. In [51], authors proposed and evaluated a seamless flow mobility management architecture (SFMMA), that tries to maximize the network throughput by allowing different kinds of network interfaces at the same time. To keep the low latency and packet loss rate, this architecture schedules messages according to three different kinds of applications: safety, comfort, and user. This architecture assumes that all vehicles move in urban environments executing different classes of applications. Two group-based network mobility management schemes (FP-NEMO and IFP-NEMO) for vehicular networks were proposed in [52] aiming to improve the handover performance of NEMO. These management schemes implement an approach that establishes multiple tunnels at the same time to be used by a group of passing-by vehicles. This approach aims to decrease the handover latency by pre-established tunnels only with vehicles that share the same geographic characteristics. Performance studies conducted through simulation and analytical models showed a performance improvement achieved by the decreasing of the signaling overhead, the packet transmission

cost, and the handover latency.

Park *et al.* [53] proposed a scheme to deal with the problem of fast IP mobility. In this scheme, several interfaces with wireless capability are considered to eliminate the packet loss problem in case of fast handover. These interfaces extended the HMIPv6 standard [54] to implement a multi-tunnel approach between HMIPv6 MAP and mobile gateways. Following this proposal, it is possible to overcome some performance limitations (e.g., handover latency and packet loss) from HMIPv6 and MIPv6.

Carvalho *et al.* [55] studied the effects of both centralized and distributed mobility strategies in vehicular networks. Both approaches are evaluated through several vehicular environments that consider Mobile IPv6 and Dynamic Mobile IP Anchoring models. Conducted performance studies to evaluate the behavior of these strategies concluded that distributed approaches achieved better results regarding data loss and delay when compared to centralized methodologies.

B. Mobility Mechanisms for V2I Communications

In vehicular networks, a direct connection between vehicles and roadside infrastructure may not be available. For this reason, conventional MIPv6-based solutions to deal with mobility management must be adapted to be applied. Peng *et al.* [56] proposed a scheme to allow the integration of VANETs with fixed IP networks. To accomplish such task, this scheme considers several parameters: (i) streets layout; (ii) distance between vehicles; and (iii) base stations with the ability to manage vehicles mobility. It also implements a novel approach, allowing multiple base stations to communicate simultaneously with destination vehicles closer to them. Performance studies showed that with this approach it is possible not only to improve the network connectivity but also the delivery ratio.

Clustering for an Open Inter-Vehicle Communication Networks (COIN) [57] aims to enable mobility functionalities without the need of a fixed infrastructure. This is accomplished by an approach where the cluster head selection is performed taking into consideration the drivers intentions and the constant changes of the distance between vehicles, defining a stable clustering strategy. In [58], authors proposed a location-aware framework to deal with reactive mobility management. This framework is based on mobility predictions in order to optimize MANET protocols to be deployed in VANETs. This framework aims to reach a kinetic mobility management in order to suppress the periodic beaconing process, which is widely considered by ad hoc protocols to mobility adaptation. With this approach, the time interval during the mobile topology is correctly anticipated.

Region-based location-service management protocol (RLSMP) [59] was proposed to takes advantages of nodes location to build geographical clusters. With this approach, location information is only restricted to a set of nodes belonging to a specific geographical cluster in the network. Then, RLSMP defines as home agent the central cell of the cluster. This agent is responsible to store and update the current location information about all nodes that belongs to its

supervision. Vehicular Ad Hoc Route Optimization for NEMO (VARON) [60] enables secure communications between moving vehicles without the need of an infrastructure. This approach allows establishing a secure hop-by-hop binding procedure using cryptographically generated addresses and public keys, which provides a security level similar to the IPv4 by reusing Mobile IPv6 security concepts. Conducted studies shown that VARON is effective in dense scenarios but inefficient for sparse scenarios.

In [61], authors proposed an architecture to minimize the handover time by performing flow management operations based on application classes for vehicle communications. These applications classes are considered to set the minimum requirements to perform the handover process. To help in this process the flow manager examines the status of active connections that considers Wi-Fi, LTE (Long Term Evolution) and 802.11p.

C. Discussion and Open Issues

The high mobility of mobile nodes raises several limitations, like the significant increase of the number of hops needed to deliver messages to their final destination, that contributes to the handoff degradation performance. Hence, mobility models (e.g., random waypoint) consider arbitrary direction and speed selection to make handoff decisions,

which makes these models not suitable for performance evaluation due to their incapacity to deal with mobility. This section aimed to provide a sampling of contributions with the common objective of taking advantages of nodes mobility and network topology flexibility to improve vehicular communications.

As future research directions on this field, and to continue increasing the confidence of vehicular networks, mobility models must be capable to deal with multiple requests competing at the same time for the same limited bandwidth, which may raise security issues. Measures for protecting data from unauthorized access and proper address configuration can be implemented. Another possible solution to solve this problem is to afford mobility models with manage capabilities to balance the priority of safety info and user requests. Finally, protocols executing on the transport and application layers need to be adapted and optimized to deal with mobility and perform correctly in vehicular environments.

Table I offers a perspective of the meaningful approaches to deal with mobility in vehicular networks, highlighting the most important achievements and drawbacks of each method. A comparison between all the proposals is also presented in this table.

Table I – Summary of different approaches to deal with mobility in vehicular networks.

References	Route Optimization	Signaling	Latency	Packet loss	V2V optimization
[40, 41]	<ul style="list-style-type: none"> The communication between entities (i.e., mobile router and home agent) is established through a two-directional tunnel. 	<ul style="list-style-type: none"> The local fixed nodes request that each mobile router to execute the routing optimization process with their corresponding node considering MIPv6. 	High	High	No
[42]	<ul style="list-style-type: none"> A two-directional channel is setup to allow participating entities (i.e., mobile router and home agent) to communicate. 	<ul style="list-style-type: none"> The MR nests behind a root-MR and updates its Nest Gate Table, by sending an Unsolicited Neighbor Advertisement. 	Low	Low	No
[43]	<ul style="list-style-type: none"> Proxy-Mobile Router, creating a tunnel to the corresponding node. 	<ul style="list-style-type: none"> Each time a mobile router moves to a different home network it establishes a new point of connection setting up a new care address. After that, it informs its home agent by sending a binding update. 	Low	Low	Yes
[47]	<ul style="list-style-type: none"> Divides vehicles into different clusters; Create different mobile networks where intra-communication is allowed; Communications in the same cluster is performed by some kind of ad hoc routing protocol. 	<ul style="list-style-type: none"> Nodes in a cluster are classified according to their functionality. Center nodes provide mobile router functions. Head nodes are vehicles in the front of the cluster and consequently tail nodes are nodes in the end of the cluster. Any other nodes are considered general nodes. 	Low	Low	Yes
[49]	<ul style="list-style-type: none"> Mobile routers, with the help of assistance nodes, are responsible to get channels states in order to perform address changes before the handoff process takes place. 	<ul style="list-style-type: none"> It considers different metrics (e.g., position, speed, and direction) to create clusters of nodes. In each cluster a node act as the mobile router, while others have to communicate through it to establish a connection with the backbone. 	Low	Low	Yes
[50]	<ul style="list-style-type: none"> The mobile router and the home agent communicate with each other considering a bi-directional tunnel allowing packets to be forwarded through multiple home agents with multiple levels of encapsulation. 	<ul style="list-style-type: none"> Signaling messages are needed to establish the optimal path. 	High	High	Yes

[51]	<ul style="list-style-type: none"> The Local Mobility Anchor (LMA) and the Mobile Access Gateway (MAG) establish a IP-in-IP bidirectional tunnel to forward all data traffic belonging to the Mobile Nodes; No bi-directional tunnel is established between the MAG's. 	<ul style="list-style-type: none"> Mobility-related layer 3 (L3) signaling messages are exchanged considering a wireless link; 	Low	Low	Yes
[52]	<ul style="list-style-type: none"> Each mobile access gateway (MAG) is configured with its own Neighboring MAG List allowing knowing which mobile routers can be handed over. Bulk messages are introduced to allow the pre-establishment of tunnels between groups of mobile routers and MAGs. 	<ul style="list-style-type: none"> FP-NEMO was proposed to deal with signaling burden. It establishes multiple tunnels simultaneously for a large group of passing-by vehicles sending single tunnel-establishment messages. 	Low	Low	Yes
[54]	<ul style="list-style-type: none"> Mobile nodes establish a connection with the Mobility Anchor Point in order to forward packets through a two-directional tunnel. 	<ul style="list-style-type: none"> Signaling exchanges required that nodes update their location; 	Low	Low	Yes
[56]	<ul style="list-style-type: none"> Base stations are placed at the end of road intersections allowing establishing a one-dimension ad hoc network, which represents a multi-hop cell. 	<ul style="list-style-type: none"> Signaling packets are broadcasted through base stations to the related ad hoc network. 	Low	Low	Yes
[57]	<ul style="list-style-type: none"> Clusters have to choose a head node. This election is performed take into consideration the dynamics of the network and drivers intentions. 	<ul style="list-style-type: none"> Use of driver intentions as input to the clustering algorithm. 	Low	Low	Yes
[59]	<ul style="list-style-type: none"> Clusters are created taking into account nodes location. Following this proposal, it is possible to perform several important tasks, such as message aggregations, which is responsible to overcome the problem related with the huge number of controls signals. 	<ul style="list-style-type: none"> Nodes use GPS devices to map their location in the grid and calculate in which cluster cell they are. Network nodes have full knowledge of the cluster, grid, and cell sizes. 	Low	Low	Yes
[60]	<ul style="list-style-type: none"> Intra-NEMO optimization. 	<ul style="list-style-type: none"> Generated by the cryptographic system. 	Low	Low	Yes

IV. TRAFFIC MANAGEMENT

The design and implementation of traffic management solutions are expected to improve traffic flows, contributing for the reduction of traffic jams and accidents. With flows optimization, it is also possible to reduce resource consumption and vehicles emissions [62]. Usually, traffic management is achieved taking into account how routing protocols operate and how they manage data. Based on these two features, proposals to deal with traffic management can be divided into a taxonomy considering two main activities: Prediction and Optimization (Fig. 2). To enable the Prediction process, road traffic information must be collected using some kind of methodology. In [63], authors presented a taxonomy for road traffic information collection that is used to perform traffic prediction functionalities. According to this taxonomy, predictive methodologies may gather data using analytical models [64, 65], fixed sensors [66], mobile phones [67, 68], or mobile devices (e.g., smartphones) combined with GPS receivers [69-71]. After the prediction process, the collected information must be evaluated by some kind of routing control [72-74] or traffic signal control [65, 75] methodology in order to perform some kind of traffic optimization strategy. Then, vehicles driven by humans can use this information to reduce roads congestion. In this section, the most important contributions for both activities are presented and discussed. Afterwards, some open issues are also identified aiming to be a starting point for the proposal of new methodologies to deal with traffic management operations and issues.

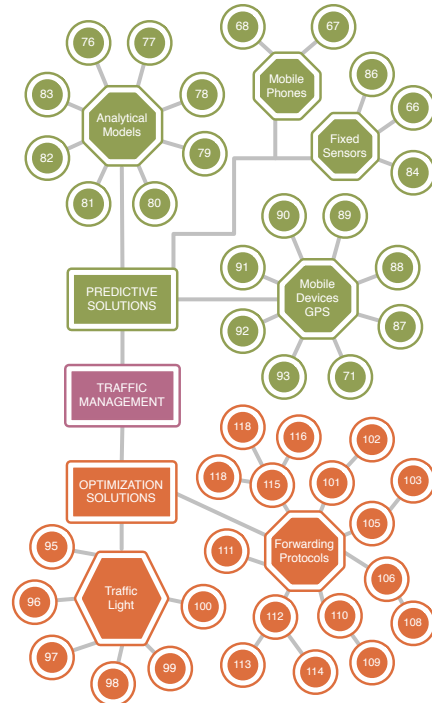


Fig. 2. Taxonomy of traffic and route solutions to perform management and monitoring functions on vehicular networks.

A. Traffic Prediction in Vehicular Networks

Several ITS applications consider prediction methods to determine how flows (e.g., path, link, and nodes) change with time and traffic intensity. The information collected by such methods can be used by traffic systems to provide real-time information. Commonly, traffic models consider three different measures to model traffic streams: speed, nodes density, and nodes flow. This sub-section overviews the most relevant proposals related with traffic prediction for vehicular communications, grouping them according to the way road traffic information is collected.

Analytical models may be proposed to study traffic models in different scenarios without the need of an infrastructure to collect information from the network. Castillo *et al.* [76] proposed a graph theory-based methodology supported by two approaches (i.e., algebraic and topological) that manages to solve the observability problem. Such methodology determines which flow should be considered after the observation process, independently of route choice probabilities. Obtained results shown that a topological approach achieves better results, since it consumes less network resources and presents no rounding errors. In [77] a modeling framework for urban traffic system was proposed. This framework allows studying the structure of urban traffic systems and understanding nodes interactions, defining in a systematically way the necessary components and their behavior to enable driver simulations. To describe the structure and components behavior a multi-level Petri net-based formalism [78] was considered. A cellular automata (CA) approach to build traffic mobility models was proposed in [79]. This approach provides rules for grouping vehicles motion based on a traffic signal coordination model of road intersections. An aggregation methodology to predict traffic flows in vehicular environments was proposed in [80]. To perform the prediction task, this methodology bases its operation on four different parameters: moving average (MA), exponential smoothing (ES), autoregressive MA (ARIMA), and neural network (NN) model. All parameters consider the traffic information collected over several days (24h/day), which are generated taking into account three different time series (i.e., weekly, daily, and hourly). Then, the NN parameter collects the prediction of each model in the aggregation stage to give a final prediction. An adaptive hybrid fuzzy rule-based system (FRBS) [81] was proposed to model and forecasting traffic flows in urban arterial networks. It considers powerful structures with capacity to store data to be capable to handle faults and unpredictability. It can perform either online and offline thanks to the implementation of a genetic algorithm and an expert's knowledge model. A traffic prediction model to control and coordinate urban traffic networks was proposed in [82]. This model takes advantages of a mixed-integer linear model to increase network optimization. Conducted studies through simulation shown the accuracy of this model in reducing the computational complex allowing increasing its applicability in real environments. A theoretical framework to estimate traffic speed was proposed in [83]. It combines low-resolution position data with other

data sources to solve the problem of some probe vehicles in providing accurate positions. With this approach, this framework manages to estimate traffic speed in a more accurate way.

Another way to predict traffic behaviors and create optimized solutions is to collect data from moving vehicles using fixed sensors placed at roadsides. By using these devices, it is possible to collect several metrics, such as vehicles current speed, the number of passing by vehicles, or vehicles flow. Following this data collection methodology, a framework based on non-conventional techniques to predict speed at single-loop detectors is proposed in [66]. From the framework predictions, it is possible to obtain a length-based vehicle classification that are further compared with concurrent measurements from video and dual-loop detectors. Tyagi *et al.* [84] proposed a traffic flow estimation system that gathers information about moving vehicles from a single roadside microphone. Such microphone allows gathering tires and engine noise, occasional honks, among others sounds. The collected sounds are optimized using algorithms to extract short-term spectral features. This optimization allows to classify traffic flows according to three different density states: Jammed (0-10 km/h), Medium-Flow (10-40 km/h), and Free-Flow (40 km/h and above). To improve the optimization process an approach is proposed in [85]. This approach considers the Cambridge Systematics from NGSIM [86] to collect traffic information (e.g., flow, density, and speed) from vehicle trajectories.

Another possible solution to collect traffic information is to exploit mobile phones. To perform such task, they should send from time-to-time, measurement reports to the core of the cellular network. Such approach avoids the installation and preservation of fixed infrastructures and sensors. Following this approach, Valerio *et al.* [67] considered a cellular network infrastructure to be used as the base of a system designed to estimate road traffic. This task is accomplished by collecting signaling messages from the mobile network. Another system to collect real-time urban traffic was proposed in [68] considering the LochNES (Localizing and Handling Network Event Systems) framework to collect information about buses and taxis instantaneous position, providing information about traffic road. This platform was deployed and evaluated in a real environment (Rome, Italy).

Mobile phones may be combined with vehicles equipped with global position system (GPS) devices and antennas. Such approach allows gathering vehicles positions and sending data to dedicated servers with a global system for mobile communications (GSM) transmitters. Li *et al.* [71] proposed a method to determine recurrent congestion points using historical probe car data. Such method was experimented in Beijing, during 57 days, considering 7000 taxis. With the analysis of the proposed method several evaluation models for recurrent congestion points were proposed. In [87], authors proposed a sensing estimation algorithm that implements a monitoring center for traffic estimation. This monitoring center receives from probe vehicles location and speed information updates. Probe vehicles are equipped with GPS

receivers in order to know their current speed and location. Conducted studies in Shanghai, with 4000 taxis, shown that behind the probe data exist hidden structures with traffic condition matrices. Kang-Ching *et al.* [88] also exploit probe vehicles equipped with GPS devices to optimize traffic status estimation. Data assimilation techniques and Newtonian relaxation methods are considered to integrate probe data into macroscopic traffic models. In [89] a management system (PRTMS) for VANETs was proposed aiming to predict traffic flows considering a communication infrastructure based on the IEEE 802.11p standard. This approach performing together with a modified linear prediction algorithm allows PRTMS to be deployed in scenarios with multiple road intersections. A central controller is also implemented to detect congestions and re-route vehicles in case of traffic congestion. DTMon [90] was proposed as a dynamic traffic monitoring system to gather information about traffic conditions. To accomplish such task, it uses roadside infrastructures that collect traffic information from moving vehicles and generate reports to traffic management systems. Rong Du *et al.* [91] proposed two patrol algorithms and a sampling rule based on the relation between the disparity of samples and traffic estimation errors, which allows to set the paths of floating cars in order to make them participate in traffic monitoring functions. Conducted studies shown that the sampling rule combined with a patrol algorithm achieves to reduce estimation errors. In [92] authors proposed a protocol specifically designed to send security messages aiming to improve the network quality of service. These messages are sent assuming that all participating vehicles have GPS devices allowing them to know their exact location when experiencing some failure or accident. When such kind of situation occurs, vehicles broadcast their position to vehicles behind. This approach allows determining the focus of traffic congestion enabling a geocasting packet transmission approach. GeoWave [93] is a network protocol that uses IEEE 802.11p to exchange useful messages that are used by an active/passive safety system. With GeoWave vehicles exchange crucial information with their neighbors or with Road Side Units (RSUs), enabling the network infrastructure to continuously gather information about traffic conditions. In [94], authors introduced a predictive system to calculate the best path between two points. This system is capable to deal with the unique characteristics of different kinds of obstacles and road structures while planning the optimal path to be followed by vehicles. This system also implements a quadratic model with a predictive controller, allowing solving an important issue related with the two-dimensional obstacle avoidance. To model the proposed system, authors considered CarSim vehicle model.

B. Traffic Optimization in Vehicular Communications

In the literature, the most efficient and commonly considered approaches to deal with traffic optimization are divided into two classes: traffic light control and routing algorithms for vehicles. Traffic light control can be described as a joint decision on the duration of signal phases associated to each signalized intersection in the network. It can be

implemented considering a fixed or an adaptive-time method. When a fixed-time method is considered, the history of traffic statistics is used to set a cycle time and the duration of one light, ignoring the changes in the traffic conditions. On the other hand, adaptive methods set the amount of time of a cycle and the duration of one light according to real-time information about traffic conditions. Routing algorithms for vehicles are used to inform drivers about optimal routes free from traffic congestion, taking into account a set of constraints such as shortest-path or time intervals.

Diakiki *et al.* [95] proposed a multivariable regulator approach (TUC) to deal with traffic signal control in urban scenarios. It considers the store-and-forward paradigm to formulate the urban traffic control problem. It also considers a linear-quadratic regulator theory to create a network-wide signal control suitable for roads with a huge level of congestion. In [96] a hybrid strategy for real-time traffic signal control for urban scenarios was proposed. This approach adapts its functionality based on traffic conditions. If a road is under saturated signalized junctions, traffic signal is controlled using a real-time Webster-type demand-drive strategy. When the road is close to saturation, this strategy changes its behavior to control signalized junctions with TUC. A technique to control real-time signals was evaluated through an API proposed in [97]. This technique allows detecting traffic fluctuations in real time since it considers a dynamic programming approach combined with adaptive signal control methodologies.

Zegeye *et al.* [98] proposed a receding-horizon parameterized (RHP) traffic control approach that combines prediction adaption and non-linear models with faster computation speed. This approach also implements a theoretical strategy to design control laws for variable speed limits and ramp metering. An architecture that bases its operation in Markovian properties combined with geometric fuzzy sets was proposed in [99]. In defines that all agents have equal decision capabilities, and their operation is based on five modules that operates concurrently. Agents are associated to an intersection and receive information from sensors, which allow them to calculate the duration of green phases. To perform such task, they consider the results gathered by different modules. The data collection module determines the queue count, while the communication module regulates the status of each neighboring intersection. All this information is put together with an average flow rate. Oliveira *et al.* [100] proposed a framework to deal with multi-agent control of linear dynamic systems. Such approach allows breaking down a centralized model considering distributed agents to solve small parts of the predictive control problem. To achieve this goal, each agent senses and controls the variables for its part of the problem, and communicates with its neighbors to get their variables in order to coordinate their actions.

StreetSmart [101] traffic is a platform that considers standard GPS driving aid to effectively discover and disseminate traffic congestion routes to drivers. This platform was designed to only exchange information on areas with unexpected traffic conditions. To determinate traffic patterns

this platform uses a combination of clustering and epidemic communications. It allows each vehicle to build a speed map containing other vehicles speed in order to transmit it to its neighbors. Shinji *et al.* [102] proposed an automobile control method that attenuates the effects of traffic congestion by taking advantages of an ad hoc communication methodology among vehicles. Each vehicle shares information about traffic condition in order to allow other vehicles to calculate a suitable congestion free route. BeeJamA [103] is a distributed traffic control model that controls vehicle traffic based on Bee Hive routing algorithm [104]. In this model, vehicles are guided under a decentralized control system. Hussain *et al.* [105] proposes a protocol to manage congestion situations and avoid deadlocks in urban environments. This is accomplished by guiding vehicles to routes clear from congestion, while managing congestion and avoids deadlock situations. In case of congestion situations (e.g., accidents) the protocol reacts using the infrastructure placed at traffic lights to collect information about nearby vehicles and neighboring infrastructures, guiding vehicles to their destination through least congested routes. TraffCon routing algorithm [106, 107] was proposed to deal with traffic congestion problem seeking to improve road capacity and decreasing fuel consumption and trip times. To deploy TraffCon, each vehicle must be equipped with a GPS receiver connected to some kind of wireless computing device with an interface that can show to the driver useful information about traffic conditions. By allowing direct communications with individual vehicles, this routing protocol intends to exert greater influence over the transportation system. *iCAR-II* routing protocol [108] was proposed to enable data communications between vehicular applications and Internet services. This protocol is setup in vehicles allowing them to forecast the existence of local connectivity and to update location servers with crucial and real-time information. With this implementation *iCAR-II* achieves to build a global and scalable network topology.

Backfrieder *et al.* [109] proposed a traffic optimization system based on a novel estimation algorithm, called Predictive Congestion Minimization in Combination with an A* (PCMA*). This algorithm is designed to calculate routes for users that are far away from their final destination. This implementation may bring significant advantages, since users can early react to potential jams far away from congestion points. To perform such task, this proposal uses a wide area timely notification approach, which takes into consideration the current state of roads. To perform traffic optimization in VANETs, a protocol called Fuzzy Bacterial Foraging Optimization Zone Based Routing (FBFOZBR), was proposed in [110]. This protocol tries to find, in a short period of time, the most stable and short route to a target under uncertain conditions. To accomplish such task, it takes advantages of three techniques: (i) Zone Based Routing (ZBR) to provide stability; (ii) Bacterial Foraging Optimization (BFO) calculates shortest routes; and (iii) fuzzy logic deals with uncertain conditions. In [111], authors proposed an algorithm capable to deal with path finding and route optimization between two points free of traffic collisions. Aiming to

achieve an optimized performance, the proposed algorithm considers a system composed by three distinct models: prediction of destination points, regions formation, and optimized route selection. Li *et al.* [112] proposed AQRV routing protocol, which as the ability to select which intersection path is the best for a vehicle to deliver data to its final destination. It considers three metrics: the connectivity probability, packet delivery ratio, and delay. In other words, the best path for a vehicle to follow is the one that presents the higher connectivity probability and delivery ratio with the lower delay. Then, authors considered an ant colony optimization methodology to solve the problem of route selection.

Gupte *et al.* [113] proposed a model, called VANET-based Autonomous Management (VAM), that performs routing decisions based on the travel paths of nearby vehicles. This model allows vehicles to exchange information about route selection, congestion and traffic alerts, which allow them to make a decision about the best path to select. It also considers traffic lights controllers to solve congestion situations, which results on a dynamic shift of the traffic patterns considering not only vehicles destinations but also road conditions. Two delay-tolerant routing algorithms to deal with traffic in vehicular networks were proposed in [114]. The first one, delay-bounded minimum-cost forwarding (D-Greedy), is devoted to deal with local changes of traffic conditions focusing on the number of vehicles and their speed, while the second one, D-MinCost dedicates its focus to global traffic conditions, calculating vehicles speed and density in the entire network. Both algorithms contribute for the reduction of the number of transmission needed to deliver messages to their final destination. Prakash *et al.* [115] proposed a path selection algorithm that aims to reduce not only the trip time but also the fuel consumption. To accomplish this goal, this algorithm ensures the best path selection by combining information about origin and destination of each vehicle with an approach where vehicles could choose a new direction at each road intersection. An opportunistic traffic management system was proposed in [116] to deal with traffic optimization in vehicular networks. It uses vehicles to exchange individually crowd-source traffic information in order to dynamically recalculate new routes. This work also quantified the effects of deploying a decentralized traffic-based navigation system by performed real experiments in Portland (USA) downtown.

In [117], a traffic optimization data driven approach was proposed to deal with the control of vehicles equipped with wireless communication devices. This proposal manages to overcome several V2V communication issues, like limited communication range or input saturation, by exploiting recent advances in approximate/adaptive dynamic programming (ADP). Won *et al.* [118] proposed a jam control protocol that considers vehicle-to-vehicle communications and a three-phase traffic theory to detect and avoid traffic jams. To calculate traffic jams dynamics, a fuzzy inference model is deployed together with a V2V-based jam detection algorithm. By dealing with traffic jams as a dynamic phenomenon instead of a binary event, allow this proposal to overcome some issues

regarding mitigating phantom jams. In [119], a congestion control strategy is proposed to deal with packet loss in high-congested road intersections. This approach exploits roadside units, placed at road intersections, to collect, filter, and cluster warning messages trying to decrease the delivery delay and the drop ratio of warning messages. By following this approach, this strategy is capable to reduce the number of traffic collisions by significantly increase the number of warning messages delivered to passing-by vehicles.

C. Discussion and Open issues

Solutions for dealing with network flows and node density take into consideration two phases: prediction and optimization. Regarding the prediction phase, several methodologies are considered to collect data. For example, analytical models produce optimal results when dealing with small networks. However, they have several limitations dealing with large-scale networks. To overcome this limitation, mesoscopic and macroscopic models may be considered. Fixed sensors are an expensive solution when compared to analytical models and are very sensitive to noise. Mobile devices allow building cost-effective services, since they are commonly used and cellular networks have a wide coverage. However, it is necessary to create additional

filtering algorithms to deal with the differences between terminals held by pedestrians and those that are located inside vehicles. GPS receivers integrated in smartphones or tablets may be used to replace mobile devices aiming to provide more powerful solutions to be deployed in remote regions. Table II provides a summary and offers a comparison analysis between the above-described approaches to deal with traffic estimation. In the other hand, when dealing with traffic optimization, two kinds of approaches were considered: traffic signal control and vehicular routing control. Traffic signal control proposals contribute to the optimization of the signal-phases duration at each intersection improving traffic flow. Finding an optimal choice of green periods, it is a very challenging task due to flow variations and the need of real time computations. Vehicular routing control aims to provide optimal management services as well as personal navigation solutions. Because new orders arrive in an arbitrary way, solutions for vehicular routing control require a re-optimization process. For further investigations, the major challenge is the proposal of fast algorithms that present low memory consumption. Table III summarizes and presents a comparison analysis between the above-described approaches to deal with traffic optimization.

Table II - Summary of different kinds of approaches to deal with traffic estimation/prediction.

How data is collected	References	Conceptual characteristics	Advantages and Limitations
Analytical Methods	[76]	<ul style="list-style-type: none"> The information is updated when items information is available considering a step-by-step methodology. 	<p>Advantages</p> <ul style="list-style-type: none"> May be implemented to assess different what-if scenarios without the need of installing sensors and roadside infrastructures. <p>Limitations</p> <ul style="list-style-type: none"> Limited to small networks; Cannot provide exact and optimal solutions;
	[77]	<ul style="list-style-type: none"> Agent based microscopic simulation; Vehicles are defined as mobile agents and their interactions with the vehicular environment are used to set the network traffic. 	
	[79]	<ul style="list-style-type: none"> Street segments are built based on road crossings and modeled following the NaSch model; To increase the system feasibility and deal with vehicles at road intersections, a set of additional rules are defined taking into consideration traffic lights placed at crossroads. 	
	[80]	<ul style="list-style-type: none"> Considers all the information collected by three different traces of traffic: hourly, daily, and weekly; Predictions are made taking into consideration the responses of three models: moving average, exponential smoothing, and autoregressive moving average. 	
	[81]	<ul style="list-style-type: none"> Considers powerful structures with capacity to store data to be capable to handle faults and unpredictability; It can perform either online and offline thanks to the implementation of a genetic algorithm and an expert's knowledge model. 	
	[82]	<ul style="list-style-type: none"> Uses a mixed-integer linear model to solve the optimization problem; Divides the network into small sub-networks to enable multiple distributed controllers. 	
	[83]	<ul style="list-style-type: none"> To solve the accuracy problem of vehicles location this proposal combines a set of data sources with flat-resolution position data. 	

Fixed Sensors	[66]	<ul style="list-style-type: none"> It classifies vehicles according to their estimated speed considering single-loop detectors combined with some classification methodologies used in dual-loop detectors. 	<p>Advantages</p> <ul style="list-style-type: none"> Real data is collected in real-time, which allows estimating traffic flows in an accurate way. <p>Limitations</p> <ul style="list-style-type: none"> Costs involving sensors installation and maintenance; Sensors have specific properties such as sensibility to noise and limited coverage; They are design to be deployed only in highways and urban scenarios.
	[84]	<ul style="list-style-type: none"> Estimates the traffic density classes considering cumulative roadside acoustic signals and a model that determines probability distributions based on traffic density stages. 	
	[85]	<ul style="list-style-type: none"> Bases its operation on a 2D stochastic signal determined through an analytic model that is capable to deal with mean-square errors and sensor spacing curves; It is deployed in environments that need an optimal sensor performance. 	
Mobile phones	[67]	<ul style="list-style-type: none"> Cellular network infrastructures are used as the base of the system operation and allow collecting signaling messages that will be used to perform traffic estimation functionalities. 	<p>Advantages</p> <ul style="list-style-type: none"> The high popularity of this kind of devices allows collecting data from traffic conditions without the installation of road sensors. <p>Limitations</p> <ul style="list-style-type: none"> Needs to implement a filtering process to distinguish pedestrians from vehicles. It is less accurate then GPS.
	[68]	<ul style="list-style-type: none"> Is proposed to urban scenarios where real-time traffic is collected by a framework that considers buses and taxis instantaneous position to estimate road traffic conditions. 	
GPS Receivers	[71]	<ul style="list-style-type: none"> Traffic estimation models consider vehicles travel abilities and links speed to determine and evaluate congestion levels; 	<p>Advantages</p> <ul style="list-style-type: none"> By using GPS receivers traffic flows are collected in real time, which provides accurate information from each road segment. <p>Limitations</p> <ul style="list-style-type: none"> Limitations in terms of coverage due to the limited number of probe cars; It also as to deal with privacy constraints.
	[87]	<ul style="list-style-type: none"> It tries to solve an issue related to the lack of traffic information in some traffic estimation conditions through the use of techniques that consider offline data analytics algorithms. 	
	[88]	<ul style="list-style-type: none"> Vehicles are exploited to increase the traffic estimation feasibility. Probe data are integrated into macroscopic traffic models through data assimilation techniques. 	
	[89]	<ul style="list-style-type: none"> Traffic prediction flows are calculated based on a communication infrastructure deployed using the IEEE 802.11p standard. It uses a modified prediction algorithm to support scenarios with multiple intersections. A central controller is also implemented to detect congestions and re-route vehicles in case of traffic congestion. 	
	[90]	<ul style="list-style-type: none"> Traffic conditions are estimated based on several reports collected by roadside devices that are delivered to management systems. 	
	[91]	<ul style="list-style-type: none"> Implements an approach that is capable to overcome estimation errors that arise from samples disparity; This approach bases its operation on two patrol algorithms that set the path of floating cars in order to force them to participate in the estimation process. 	
	[92]	<ul style="list-style-type: none"> Secure messages are forwarded aiming to increase the network QoS; This process is performed by a geocasting protocol that assumes that all participating vehicles have GPS devices to know their own location. 	
	[93]	<ul style="list-style-type: none"> Uses IEEE 802.11p to exchange useful messages that are used by an active/passive safety system. Vehicles exchange crucial information with their neighbors or with Road Side Units (RSUs), enabling the network infrastructure to continuously gather information about traffic conditions 	

Table III – Summary of different kinds of approaches to deal with traffic optimization.

Optimization Approach	References	Conceptual Characteristics	Advantages and Limitations
Traffic light control	[95]	<ul style="list-style-type: none"> Considers the store-and-forward paradigm to formulate the urban traffic control problem; It also considers a linear-quadratic regulator theory to create a network-wide signal control suitable for roads with a huge level of congestion 	<p>Advantages</p> <ul style="list-style-type: none"> This approach allows controlling traffic flows by considering a combination between the decisions of the duration of signal-phases assigned to each signalized intersection in the network. <p>Limitations</p> <ul style="list-style-type: none"> Traffic flows changes and computation time limitations make the provision of a global optimization for the network a very difficult task.
	[96]	<ul style="list-style-type: none"> Implements an approach to deal with traffic congestion by implementing a strategy where road intersections are controlled by driver's demands. 	
	[97]	<ul style="list-style-type: none"> It implements a technique where real-time signals are controlled by adaptive signal control methodologies combined with dynamic programming approaches. 	
	[98]	<ul style="list-style-type: none"> It proposes a traffic control approach to adapt predictions combining non-linear models with a theoretical strategy to design control laws able to deal with variable speed limits and ramp metering. 	
	[99]	<ul style="list-style-type: none"> Adopts a distributed multi agent-based approach; Geometric fuzzy sets of traffic are combined with Markovian properties to deal with multiple levels of ambiguity found on traffic controllers. 	
Forwarding protocols for vehicles	[101]	<ul style="list-style-type: none"> GPS devices are used to help this platform to discover and disseminate through the network road congestion alerts; Communications follow an epidemic approach to determine traffic patterns. 	<p>Advantages</p> <ul style="list-style-type: none"> Allow vehicle drivers to choose the most suitable route for their purposes. <p>Limitations</p> <ul style="list-style-type: none"> Requires the use of fast algorithms that manages the memory space. Algorithms design is more complex.
	[102]	<ul style="list-style-type: none"> The effects of traffic jams are reduced through the implementation of an automotive control method where each network node gather traffic information each time it establishes an ad hoc connection with another vehicle; This approach allows vehicles to calculate and determine a path free of congestion. 	
	[103]	<ul style="list-style-type: none"> Communication links are dynamically updated considering distributed algorithms that select the better route for each vehicle taking into consideration its destination. 	
	[105]	<ul style="list-style-type: none"> Trying to avoid road congestion this approach exploits roadside devices placed at traffic lights to collect information about passing-by vehicles; This information is also considered to solve traffic congestion situations, guiding vehicles to clear routes. 	
	[106, 107]	<ul style="list-style-type: none"> Manages to increase road capacity by considering a set of vehicles with wireless communications capabilities to spread information about the state of the network; Each vehicle must have a visual interface to show to the driver useful information regarding traffic jams. 	
	[113]	<ul style="list-style-type: none"> Routing decisions are taken taking into consideration the paths followed by nearby vehicles; At each contact opportunity vehicles exchange information about traffic jams and alerts allowing them to choose the best new path to follow. 	
	[114]	<ul style="list-style-type: none"> Proposed routing protocols have the ability to deal with traffic condition taking into consideration local and global network statistics (e.g., vehicles speed and density); 	

	[115]	<ul style="list-style-type: none"> It uses an algorithm to calculate the best path between two different locations taking into consideration the information collected by vehicles that travel in paths near from both locations. 	
	[116]	<ul style="list-style-type: none"> Uses vehicles to exchange individually crowd-source traffic information in order to dynamically recalculate new routes. 	

V. COMMUNICATIONS, DATA, AND RESOURCE MANAGEMENT

With the growing interest in vehicular communications and the maturity of routing protocols for wireless and ad hoc networks, innovative applications and services begin to be proposed. However, to design efficient applications, it is important that they take into consideration the particular characteristics of vehicular networks. For example, node positioning and connectivity, communication intermittence and fairness, latency, and resources limitation may have a huge impact on their performance. Also, the increasing number of technologies available to vehicles makes communications and resource management two of the major issues that must be solved when dealing with vehicular communications [120]. Trying to overcome these limitations it is important to adopt methodologies capable to deal with communication, resources and data management and monitoring. This section, presents a taxonomy (Fig. 3) following the above-presented methodologies, and details on the most important proposals for each one of them.

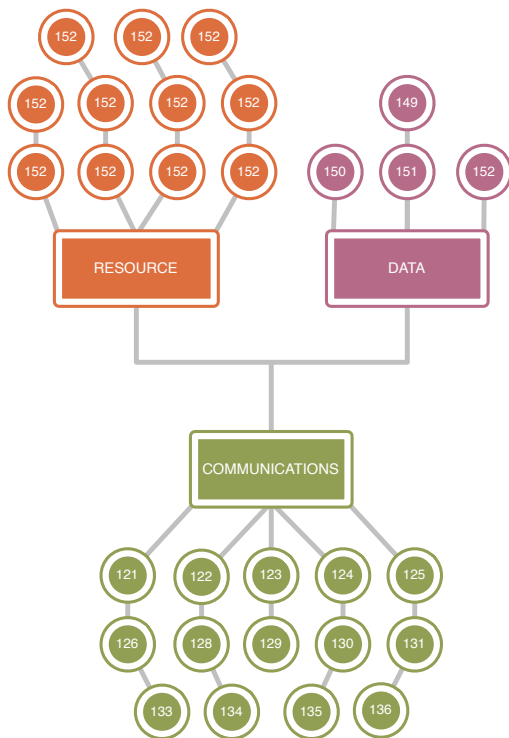


Fig. 3. Taxonomy of communications, data and resource methodologies to perform management and monitoring functions on vehicular communications.

A. Communication Management

The intermittence and latency that characterizes vehicular communications are the major responsible for the huge amount of packet loss, data deterioration, and low quality of communication channels. This problem is strengthened by the possible non-existence of a path between messages origin and destination. Trying to solve some of these issues, a framework for services and communication management, called SCM, was proposed in [121]. This framework intends to ensure that the deployed ITS services requirements are met by selecting the adequate data dissemination method and the underlying heterogeneous communication network. This goal is achieved by using two network performance-reporting techniques that consider simple policy-based procedures and metrics. MOCA [122] was proposed to enable reliable communication in vehicular environments. It takes advantages from distributed channels selection and cognitive radio technology to access the frequency spectrum. Then, it uses the information (e.g., speed and direction) gathered from moving vehicles frequency channels to predict the channel quality. To ensure an optimal channel performance MOCA employs SNR and bit error rate. In [123], authors proposed a solution to manage the network communications infrastructure by designing an algorithm that has the ability to discover roadside units based on partial information collected by vehicles. This algorithm bases its operation on the information of vehicles density combined with migration ratios. With this approach, it manages to handle traffic fluctuations. It also assumes the use of stationary, virtual, and mobile RSUs. Conducted studies consider realistic mobility traces from the city of Cologne, Germany. Authors concluded and demonstrated that to achieve an optimized performance it is not necessary to have knowledge of the full matrix of vehicles. Cao *et. al* [124] proposed a novel framework to manage communications aiming to disseminate information regarding charging stations. This framework exploits public transportation vehicles (e.g., buses) as access points to inform moving vehicles about network and charging stations condition. Such approach allows to create a low-cost and flexible communication infrastructure. Communications between vehicles are based on a publish/subscribe paradigm, which was demonstrated by authors, to be an efficient way to propagate information across the network.

Woo *et al.* developed a location mechanism called MGLSM [125] that aims to enhance mobile nodes communications. It dynamically group moving vehicles into regions according to their destination point. Each region has a fixed location server and a group leader (usually a mobile node in the center of the group). The group leader is

responsible to collect and maintain the information about the exact location of nearby vehicles. Periodically, it reports the location changes in the group to the fixed location server. Then, the location server maintains the reported information and replies to the location queries made by group members. When a foreign vehicle makes a location request, the location server performs inter-region information exchange in order to solve the tradeoff problem, providing regional proximity and binding stability between vehicles. Patil *et al.* [126] proposed a Voronoi diagram-based algorithm to place roadside units (RSUs) using as evaluation measures the delivery delay and packet loss. This algorithm places RSUs by dividing each geographical region into cells that are convex polygons. To create and define the shape of polygons this algorithm considers the maximum tolerable packet delay, which represents how far data packets can travel from an RSU to another, considering a limited period of time. Such approach demonstrated to improve the reliability of communications and increased the logical coverage area of each RSU.

A Simple Network Management Protocol (SNMP) [127] framework was proposed in [128] to perform off-board communications and control through cellular technologies. This framework combines the characteristics of the SNMP protocol with mechanisms to access territorial GSM network, allowing to create a monitoring system focused on the performance of the network. To collect information for the system, vehicles are equipped with several sensors that collect speed, acceleration, steering angle, and air temperature. Authors employed SNMP to take advantages of two classes of location: (i) based on tracking and (ii) based on mobility control. GUERRILLA Management Architecture (GMA) [129] is an SNMP-based solution that uses a cluster based management mechanism and mobile agents to create an autonomous management environment. To perform such task, nodes that share the same characteristics are aggregated into clusters managed by nomadic managers. These managers autonomously collaborate with network nodes to manage the entire network. Soo-Jin *et al.* [130] proposed an integrated wireless management system to monitor devices status. It is based on SNMP that allows the owner of a device to manage it remotely and domains an administrator to evaluate security vulnerabilities. Papalambrou *et al.* [131] presented a network monitoring implementation for DTNs that differs from diagnostic interplanetary network gateway (DING) [132] by focusing on the bundle protocol implementation. It implements monitoring mechanisms in the Bundle and lower layers allowing assessing DTNs performance. MAN4VDTN [133] is a SNMP-based solution for VDTNs that provides support to push data from VDTN nodes. In this solution, the network management system (NMS) handles the communications between network nodes using SNMP messages. The Trap Coverage Area Protocol (TPAC) [134] was proposed as a low-cost methodology to monitor vehicles communications in urban environments taking advantages of traffic cameras, usually placed on road intersections. TPAC uses roadside routers to control cameras, which seek for vehicles license plate number in order to identify them. It also

combines the concept of trap covering area with the proposal of new algorithms to maximize scalability in order to overcome the recognized vehicle tracking problem. Results demonstrated the efficiency of TPAC in reducing the communication overhead and latency. Chen *et al.* [135] proposed several fog computing methodologies to solve the problem of network load created by the growing number of vehicles. These methodologies are supported by two dynamic scheduling algorithms capable to adapt to constant network changes. To optimize communications latency and balance the cost and performance of communications, a new strategy was presented in [136]. It combines both vehicular and cellular networks, to reduce the higher latency that characterizes ad hoc connections and the energy and budget costs associated to cellular networks. The bandwidth rebating problem was solved with a two-stage Stackelberg game.

B. Resources and Data Management

Usually, vehicular network nodes have several resource constraints. The most common are related with storage and power limitations. In order to maximize nodes resource consumption and its overall performance, it is necessary to design solutions that fulfill vehicular communications requirements.

To deal with buffer constraints, a model that considers a semi-Markov distribution was proposed to be deployed in wireless sensor vehicular networks [137]. It aims to solve the problem of data transportation between sensor nodes and sinks. This model bases its decision process in a buffer allocation policy where the buffer is divided into states according to its occupancy percentage. This model also introduces a parameter that limits the buffer occupancy of each network node. This will allow to drop packets only in case of buffer saturation. Yu *et al.* [138] proposed a cloud computing architecture, where mobile nodes can share their resources with others considering three distinct cloud types: vehicular, roadside, and central. Vehicular cloud is established by a set of cooperative mobile nodes communicating with each other. Roadside cloud is established among a group of roadside units allowing mobile nodes to access resources, stored at cloud servers, located at roadside units. Finally, central cloud is setup by a set of servers maintained outside the network. To solve nodes resource competition, the proposed architecture uses a game-theoretical framework. In [139], a joint resource management scheme is proposed to perform access network selection helping on the handover decision process. This decision is taken considering the results obtained from an optimal algorithm that uses a Semi-Markov decision method. An optimal algorithm is then derived via reinforcement learning, aiming to minimize the blocking probability while maximize the system total throughput.

Cordeschi *et al.* [140, 141] designed and implemented a resource management controller that is capable to handle vehicles energy and computation constraints. This controller deals with the resource management problem by dynamically control the time-windows access of roadside units' as well as traffic flows. In [142], a cooperative resource management is

proposed to deal with bandwidth and computing resource-sharing problem. This problem was solved through a coalition game model implementation in cooperative service providers, based on a two-sided matching theory. Following this approach, the mechanism aims to improve the QoS for users by reduce the amount of consumed resources. Arani *et al.* [143] designed a resource management tool for self-organizing networks that aims to solve energy consumption problems in high populated scenarios. This is achieved by combining the proposed tool with several mechanisms to manage joint channels and power allocation procedures. In [144], a resource search and management scheme is proposed. This work aims to allow vehicular networks to perform management operations without the need of a fixed and centralized infrastructure. Such achievement is possible due to the proposal of a peer-to-peer protocol, called SMART, which discovers and manages resources allowing vehicles to self-organize, creating connections with each other to manage and share resources. Kumar *et al.* [145] proposed an architecture that allows to integrate mobile edge computing with smart grid environments. With this proposal, vehicles are able to decide which charging station are the best choice to perform charging and discharging operations. To minimize energy consumption, authors proposed a virtual machine migration approach that is implemented at the data center side. In [146], two controllers were proposed to deal with energy constraints in vehicular environments. They consider the kinetic energy of vehicles and the fuel consumption of the engine to optimize vehicle velocity. Vehicles engine, brake system, and transmission are managed by the controllers based on a real-time road feedback approach. A trust management mechanism was proposed in [147] to efficiently use vehicles physical resources (e.g., storage and power). This mechanism solves the trustworthiness problem that may lead to un-authorizing users to consume limited network resources without any intention to contribute for the proper operation of the network. This is achieved by implementing a three-manager cloud-based trust management framework. The first level, Global Trust Manager (GTM) stores and manages all vehicle's profiles. Then, the Domain Trust Manager (DTM) gets vehicles information from the GTM to assign a trust evaluation token to each vehicle that will be used by the Vehicular Trust Model (VTM) to inform neighbors about the trustworthiness of a vehicle. In [148], a framework to perform monitoring and management activities in VDTNs were proposed. It takes advantages of the unique characteristics of VDTNs to gather real time information regarding the network state. For example, it collects information about nodes buffer space, power, and statistical data regarding communication performance. To improve the overall network performance, it implements two modules: monitoring and management. The monitoring module is always seeking for nodes with buffer constraints or nodes that are diverging from the protocol. Once one of these situations occur, the management module takes actions against the misbehavior node and generates an alert informing other nodes to avoid contacts of the constraint node. Performance studies show that the use of this framework

contributes to reduce the waste of resources allowing increasing the overall network performance.

Patwardhan *et al.* [149] proposed a data management scheme where vehicles can help each other locating network resources. With this implementation, vehicles can rapidly adapt to local network changes. To enable data management, authors consider vehicles reputation and an epidemic data exchange protocol capable to establish trust relationships. Nodes reputation score is calculated based on a taxonomy of four device types (Encountered, Observed, Cooperative, and Malicious) followed by the level of cooperation. To classify nodes into this taxonomy, this scheme considers several metrics, such as frequently visited locations, mobility patterns, and information categories. In [150], a data management policy for vehicular networks was proposed. It intends to prevent the occurrence of scalability and congestion problems by handling bandwidth and unnecessary duplication data. This policy takes advantages of vehicles mobility and a context-aware service based on geographic location to estimate how important information are to end-users. It also considers a publisher/subscriber model and a cluster-based algorithm to disseminate data. Another data management framework is proposed in [151]. It aims to deal with some data processing issues, by transforming data into XML-based data, which allows in-vehicle infotainment to be easily accessed and processed. A proactive data dissemination scheme to manage critical data in vehicular data networks was proposed in [152]. To accomplish such achievement, each vehicle must broadcast packet requests to pull resources from the network. Then, this request is answered by the nearest producer. In case of critical content, vehicles use a critical data forwarding scheme, that gives them the ability to disseminate a special beacon message to their 1-hop neighbor.

C. Discussion and Open Issues

Dealing with communications, data, and resource management is a very challenging topic, since most of network nodes have to deal with resource constraints, comprising their network performance. Although all the proposals presented in this section, there are still some challenging issues to overcome. For example, the exchange of large amounts of data (e.g. multimedia content such as photos and videos) in vehicular networks is a challenging task. However, it could contribute to provide richer and detailed information to travelers about road conditions. The exchange of such kind of data between vehicles may not be an easy task due to short contact durations, which limits the amount of data that can be exchanged. Transmitting such kind of data may also lead to a high network overhead.

Regarding data management, a possible solution to facilitate data aggregation and data relevance evaluation is to develop some kind of middleware that could combine routing functionalities with data evaluation techniques. This approach can contribute to afford vehicular networks with extensible and adaptable software architectures that could be placed on the top of different applications and information systems.

Several proposals on this field begin to appear, however there is no evidence of its applicability in real scenarios.

Moreover, this table presents the most important conceptual characteristics and remarks of each method.

Table IV highlights the most important contributions related to communications, data, and resource management.

Table IV – Summary of different kinds of communication, data, and resource management approaches.

References	Main Conceptual Characteristics	Remarks
[121]	<ul style="list-style-type: none"> Uses two network performance-reporting techniques that consider simple policy-based procedures and metrics. 	<ul style="list-style-type: none"> Ensures that the deployed ITS services requirements are met by selecting the adequate data dissemination method and the underlying heterogeneous communication network;
[122]	<ul style="list-style-type: none"> Takes advantages from distributed channels selection and cognitive radio technology to access the frequency spectrum; Uses information (e.g., speed and direction), gathered from moving vehicles frequency channels to predict the channel quality; To ensure an optimal channel performance, MOCA employs SNR and bit error rate. 	<ul style="list-style-type: none"> Significant network connectivity improvement with the decrease of throughput and jitter; Surpass the TFRC-CR protocol [153] performance.
[123]	<ul style="list-style-type: none"> The network communication infrastructure is managed by an algorithm capable to discover roadside units in spite of the information collected by vehicles; It uses vehicles density and speed combined with migration ratios to handle traffic fluctuations. 	<ul style="list-style-type: none"> To achieve an optimized performance is not necessary to have knowledge of the full matrix of vehicles.
[125]	<ul style="list-style-type: none"> Enhances mobile nodes communications by dynamically grouping them into regions according to their moving direction; Each region has a fixed location server and a group leader. The group leader is responsible to collect and maintain the exact location information of nearby vehicles, while the location server maintains the reported information and replies to the location queries made by the group members. 	<ul style="list-style-type: none"> This proposal was evaluated through simulation proving that is able to provide more accurate location discovery services with lower overhead.
[126]	<ul style="list-style-type: none"> Places roadside units (RSUs) considering as criteria the packet delay and loss; Geographic locations are divided into regions considering convex polygons. 	<ul style="list-style-type: none"> The approach followed by author's results in less packet delay and lesser packet loss improving significantly the overall communications performance.
[128]	<ul style="list-style-type: none"> Manages to combine the SNMP protocol with mechanisms to access territorial GSM network; Vehicles are equipped with several sensors allowing them to collect speed, acceleration, steering angle, and air temperature. 	<ul style="list-style-type: none"> By considering the use of SNMP this proposal outperforms other proposals in terms of throughput and jitter.
[129]	<ul style="list-style-type: none"> Nodes sharing similar characteristics are grouped into the same clusters, which is managed by a single nomadic manager. Nomadic managers collaborate with other nodes to perform network management functions. 	<ul style="list-style-type: none"> Minimize management traffic and conserve wireless bandwidth by using nomadic managers.
[130]	<ul style="list-style-type: none"> The status of each network device is managed by an integrated wireless system that uses the SNMP protocol to allow the owner of the device to perform different management functionalities. 	<ul style="list-style-type: none"> Administrators are allowed to improve the security levels of their own vulnerability evaluation.
[131]	<ul style="list-style-type: none"> Implements a network monitoring approach for DTNs that differs from DING; Focuses its implementation on the bundle protocol; It implements monitoring strategies in the Bundle and lower layers allowing assessing DTNs performance. 	<ul style="list-style-type: none"> Manages to collect detailed information about network status that can be easily accessed and processed by data visualization tools.

[133]	<ul style="list-style-type: none"> Enables statistical data collection from network nodes through the SNMP protocol. 	<ul style="list-style-type: none"> Proposal of a network management solution based on the standard SNMP for VDTNs.
[137]	<ul style="list-style-type: none"> This model bases its decision process in a buffer allocation policy where the buffer is divided into states according to the occupancy percentage; Introduces a parameter that limits the buffer occupancy of each network node avoiding to drop unnecessary packets. 	<ul style="list-style-type: none"> Solves the problem of data transportation between sensor nodes and sinks
[138]	<ul style="list-style-type: none"> Vehicles may share resources with others considering three different kinds of cloud definitions: vehicular, roadside, and central; To deal with vehicles resource competition, this scheme uses a game-theoretical framework. 	<ul style="list-style-type: none"> Solve an issue regarding virtual machine migration due to nodes mobility and speed; Service-dropping rate is attenuated.
[139]	<ul style="list-style-type: none"> Proposes an optimal algorithm to perform access network selection and helping on the handover decision process; The handover decision process is formulated as a Semi-Markov Decision Process. 	<ul style="list-style-type: none"> Performance evaluation studies compare its performance with other three algorithms (Load Balance, Hight MCS, and RLwoHO) and shows that it manages to overcome their performance.
[140, 141]	<ul style="list-style-type: none"> Focuses its operation on energy and computational limitations of vehicles; Dynamically controls the roadside units' access time-windows. 	<ul style="list-style-type: none"> Helps to minimize the impact of the resource management problem.
[142]	<ul style="list-style-type: none"> Implements in cooperative service providers a coalition game model based on two-sided matching theory. 	<ul style="list-style-type: none"> Improves the QoS for users and decreases the amount of consumed resources; Solves the bandwidth and computing resource-sharing problem.
[149]	<ul style="list-style-type: none"> Vehicles help each other locating resources by implementing an approach that allow them to rapidly adapt to local network changes; Uses vehicles reputation and an epidemic data exchange protocol to establish trust relationships; Nodes reputation is calculated based on a taxonomy that comprises four device types (Encountered, Observed, Cooperative, and Malicious) followed by the level of cooperation. 	<ul style="list-style-type: none"> This approach manages to increase the resources availability by performing collaborative data exchanges between vehicles.
[150]	<ul style="list-style-type: none"> Gets advantages of vehicles mobility to determine how relevant and important information are to end-users; 	<ul style="list-style-type: none"> Prevents scalability and congestion problem by handling bandwidth and unnecessary duplication data.
[151]	<ul style="list-style-type: none"> A layer to perform management functionalities is implemented considering the Java programming language. 	<ul style="list-style-type: none"> Allows in-vehicle infotainment to be easily accessed and processed.

VI. CONCLUSION

In the last decade, several vehicular architectures have been proposed exploiting mobile nodes to enable communications in different kind of scenarios. For example, vehicular communications may be considered as a solution where a fixed infrastructure with an available path between source and destination nodes may not be available. Although all the advances known in this type of networks, there are still

challenging issues that must be overcome (e.g., short contact duration, storage capacity, limited power, latency, energy consumption). Performing network management functionalities may be a possible solution to solve some of these issues. Several approaches to deal with network management were proposed in the literature to detect network anomalies and manage network resources aiming to improve the overall network performance.

This work summarized the most important projects, frameworks, and proposals about network management and monitoring in vehicular communications. Such proposals may gather several contributions from wireless ad hoc and delay tolerant networks. Conducted studies from the presented-solutions shown that vehicular networks present significant performance gains when management and monitoring solutions are deployed in the network. This work may be considered as a starting point to study and propose more complex and efficient management and monitoring solutions aiming to increase the reliability and confidence on the use of vehicular communications.

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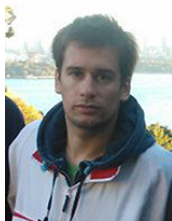
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João A. F. F. Dias was born in Covilhã, Portugal, in 1986. He is currently working toward the Ph.D. degree in Informatics Engineering at the University of Beira Interior. He is also member of the Instituto de Telecomunicações (IT) and the NetGNA research group. As a researcher, he is author or co-author of 34 papers, published on international journals and conferences, and 2 technical reports. His research interests include ad hoc networks, delay-tolerant network, Vehicular communications and architectures, and Automotive Systems.



Joel J.P.C. Rodrigues (S'01, M'06, SM'06) is a professor and senior researcher at the National Institute of Telecommunications (Inatel), Brazil and senior researcher at the *Instituto de Telecomunicações*, Portugal. He has been professor at the University of Beira Interior (UBI), Portugal and visiting professor at the University of Fortaleza, Brazil. He received the *Academic Title of Aggregated Professor* in informatics engineering from UBI, the Habilitation in computer science and engineering from the University of Haute Alsace,

France, a PhD degree in informatics engineering and an MSc degree from the UBI, and a five-year BSc degree (licentiate) in informatics engineering from the University of Coimbra, Portugal. His main research interests include e-health, sensor networks and IoT, vehicular communications, and mobile and ubiquitous computing. Prof. Joel is the leader of NetGNA Research Group (<http://netgna.it.ubi.pt>), the President of the scientific council at ParkUrbis – Covilhã Science and Technology Park, the Past-Chair of the IEEE ComSoc Technical Committee on eHealth, the Past-chair of the IEEE ComSoc Technical Committee on Communications Software, Steering Committee member of the IEEE Life Sciences Technical Community and Publications co-Chair, and Member Representative of the IEEE Communications Society on the IEEE Biometrics Council. He is the editor-in-chief of the International Journal on E-Health and Medical Communications, the editor-in-chief of the Recent Advances on Communications and Networking Technology, the editor-in-chief of the Journal of Multimedia Information Systems, and editorial board member of several high-reputed journals. He has been general chair and TPC Chair of many international conferences, including IEEE ICC, GLOBECOM, and HEALTHCOM. He is a member of many international TPCs and participated in several international conferences organization. He has authored or coauthored over 500 papers in refereed international journals and conferences, 3 books, and 2 patents. He had been awarded several Outstanding Leadership and Outstanding Service Awards by IEEE Communications Society and several best papers awards. Prof. Rodrigues is a

licensed professional engineer (as senior member), member of the Internet Society, an IARIA fellow, and a senior member ACM and IEEE.



Kashif Saleem is currently working with Center of Excellence in Information Assurance (CoEIA), King Saud University, since March 2012 as an assistant professor. He received his M.E. and Ph.D. in Electrical Engineering from University Technology Malaysia in 2007 and 2011, respectively. He took professional trainings and certifications from Massachusetts Institute of Technology (MIT), USA, IBM, Microsoft, Cisco. Kashif Saleem has authored several research publications and his professional services include - Guest Editorships, Conferences Chair, Workshops Chair, TPC Member, Invited Speaker and reviewer for several renowned international journals and conferences. His research interests are Ubiquitous Computing, Bio-inspired Algorithms, Mobile Computing, IoT, M2M Communication, WSNs, MANETs, Intelligent Autonomous Systems, Information Security.



Neeraj Kumar received the PhD degree in CSE from Shri Mata Vaishno Devi University, Katra (J&K), India. He was a postdoctoral research fellow with Coventry University, Coventry, United Kingdom. He is working as an associate professor in the Department of Computer Science and Engineering, Thapar University, Patiala, Punjab, India. He has published more than 150 technical research papers in leading journals and conferences from IEEE, Elsevier, Springer, John Wiley etc. Some of his research findings are published in top cited journals such as the IEEE Transactions on Industrial Electronics, the IEEE Transactions on Dependable and Secure Computing, the IEEE Transactions on Information Forensics and Security, the IEEE Transactions on Consumer Electronics, the IEEE Network, the IEEE Com, IEEE WC, the IEEE Internet of Things Journal, the IEEE Systems Journal, the Future Generation Computer Systems, the Journal of Network and Computer Applications, and the Computer Communications. He has guided many research scholars leading to PhD and ME/MTech. His research is supported by funding from TCS, CSIR, and UGC. He is a member of the IEEE.



Mario Lemes Proença Jr. is an Associate Professor and leader of the research group that study computer's network in the Computer Science Department at State University of Londrina (UEL), Brazil. He received the Ph.D. degree in Electrical Engineering and Telecommunications from State University of Campinas (UNICAMP) in 2005. He received the title of M.Sc degree in Computer Science from the Informatics Institute of Federal University of Rio Grande do Sul (UFRGS), in 1998. He has authored or coauthored over 90 papers in refereed international journals and conferences, books chapters, and 1 software register patent. His research interests include Computer Network, Network Operations, Management and Security and IT Governance. He has supervised 12 M.Sc. and two Ph.D. students. He has been a Master's supervisor at computer science in State University of Londrina and Ph.D supervisor in Department of Electrical Engineering at UEL.

Chapter 9

REMA: A REsource MAnagement Tool to Improve the Performance of Vehicular Delay Tolerant Networks

This chapter is based on the following paper:

REMA: A REsource MAnagement Tool to Improve the Performance of Vehicular Delay Tolerant Networks

João A. F. F. Dias, Joel J. P. C. Rodrigues, Neeraj Kumar, Valeriy Korotaev, Guangjie Han

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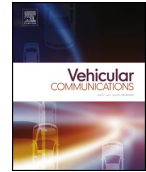
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REMA: A Resource Management tool to improve the performance of vehicular delay-tolerant networks



João A.F.F. Dias^a, Joel J.P.C. Rodrigues^{a,b,c,d,*}, Neeraj Kumar^e, Valeriy Korotaev^c, Guangjie Han^f

^a Instituto de Telecomunicações, Universidade da Beira Interior, Portugal

^b National Institute of Telecommunications (Inatel), Brazil

^c University ITMO, Russia

^d University of Fortaleza (UNIFOR), Brazil

^e Computer Science and Engineering Department, Thapar University, Patiala (Punjab), India

^f Department of Information & Communication Systems, Hohai University, Changzhou, China

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ABSTRACT

Vehicular Delay-Tolerant Networks (VDTNs) architecture was proposed to overcome some constraints faced by vehicular environments, more precisely, the highly dynamic network topology, disruption, and the absence of an end-to-end path between source and destination. Then, it uses a store-carry-and-forward paradigm based on asynchronous and a bundle-oriented communication between network nodes. To deal with the specific characteristics of vehicular environments, routing protocols proposed for wireless and ad hoc network must be adapted or new routing protocols should be designed. Usually, they are responsible for the entire self-managing of the entire network, which in certain cases may comprise the network performance. This paper presents and describes a resource management tool, called REMA, that aims to support routing protocols to minimize the consumption of network resources contributing to increase the overall network performance. This is achieved by a sophisticated scheduling approach that forwards bundles taking into account the best interests of a VDTN network. Performance evaluation studies conducted through simulation shown that REMA decreases the amount of wasted resources significantly, increases the bundle delivery ratio, and decreases the overhead ratio compared to scenarios where no additional action is performed to deal with resources consumption.

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1. Introduction

In the last decades, the automotive industry and the research community have been joined efforts to create vehicular architectures capable to be applied in a wide range of scenarios. For example, they can be used to disseminate safety information about road conditions (e.g., emergency notifications and collision avoidance) [1,2], to distribute multimedia content (e.g., images and video) [3,4], or to collect data for monitoring purposes [5]. Although the above-presented urban scenarios, vehicular networks may also be considered for remote regions or on disaster environments. In remote regions they can support communications between sparse villages, enabling non-real time services and applications [6,7]. Re-

garding to disaster scenarios, they can be used as a support infrastructure, allowing communications between rescue teams and emergency facilities [8].

Vehicular environments have unique characteristics that raise several issues that must be considered to design new approaches and methodologies. For example, nodes density, speed, and mobility lead to continuous changes on the network topology and short contacts durations [9,10]. Disruption and intermittent connectivity are also two of the main issues faced by vehicular networks. Both situations may be instigated by limited transmission ranges and interferences of wireless communications caused by physical obstacles. All these features lead to network partition and discontinuities along paths between source and destination nodes.

Trying to minimize the limitations of vehicular communications several architectures were proposed. Vehicular Ad hoc Networks (VANETs) [11] enables end-to-end data communications by exploiting vehicles and assuming that routing and forwarding protocols establish an end-to-end connectivity approach. Unfortunately, this conjecture does not solve the partition and disconnection

* Corresponding author at: National Institute of Telecommunications (Inatel), Brazil.

E-mail addresses: joao.dias@it.ubi.pt (J.A.F.F. Dias), joeljr@ieee.org (J.J.P.C. Rodrigues), neeraj.kumar@thapar.edu (N. Kumar), korotaev@grv.ifmo.ru (V. Korotaev), hanguangjie@gmail.com (G. Han).

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problems. To surpass these problems, the store-carry-and-forward paradigm from the Delay-Tolerant Network (DTN) [12] architecture may be considered. This paradigm does not need an end-to-end path between source and destination since it uses intermediate nodes to store and forward data between them to create a path over time. With this approach, delay tolerant networks not only accomplish to increase the delivery probability, but also allow a wide variety of services and applications to be deployed.

Taking advantages of the DTN store-carry-and-forward paradigm, Vehicular Delay-Tolerant Networks (VDTNs) [13] were proposed. Although VDTNs gather others contributions from DTNs, this approach distinguishes itself by presenting an out-of-band signaling methodology, with separation of control and data planes, and by placing the bundle layer under the network layer deploying an Internet Protocol (IP) over VDTN approach. This solution allows aggregating datagrams sharing the same characteristics (e.g., destination) into bundles, which are transmitted asynchronously through the network. The transmission of bundles is made using the data plane, after the data channel is reserved for a bundle by the information exchanged through the control plane.

To deal with the store-carry-and-forward paradigm, existent routing protocols must be adapted or new approaches must be proposed [14]. Different classes of routing protocols consider different solutions and information to make routing decisions in order to maximize the overall network performance. Usually, they are designed to be responsible for the self-managing of the network trying to minimize the resources consumption. However, external and sophisticated solutions should be considered to optimize the self-managing performance of routing protocols. This methodology may conduct to significant improvements regarding topology stability and traffic overhead contributing to maximize the delivery ratio and minimize the resources consumption (e.g., energy or bandwidth). With this concept in mind, this paper proposes a resource management tool for VDTNs, called REMA. It aims to optimize the overall network performance, by minimizing the amount of resources consumed, while maximizing the delivery probability. Its operation principles and design are described and its performance is evaluated through exhaustive simulation experiments deploying it together with three routing protocols: Epidemic [15], Spray and Wait [16], and GeoSpray [17]. The evaluation study of this contribution to the state of the art was conducted considering the delivery probability, the average delivery delay, the number of dropped bundles, and the protocol overhead ratio. From the performance evaluation analysis, it can be concluded that the proposed resource management tool contributes to significantly increase the overall network performance by increasing the delivery probability and reducing the amount of wasted resources (i.e., less bundles are dropped and the overhead ratio decreases).

The main contributions of this paper are the following:

- Identification and description of the most relevant strategies to deal with resources management in vehicular networks.
- Proposal of a resource management tool for VDTNs that considers a sophisticated scheduling approach.
- Implementation of the tool and performance evaluation.

The remainder of the paper is organized as follows. Section 2 overviews the VDTN network architecture and Section 3 summarizes the most important approaches already proposed to deal with resources management in vehicular and delay tolerant networks. Section 4 presents the resource management tool for VDTNs, called REMA, including its operation principles and design. Section 5 focuses on the performance evaluation of the proposed resource management tool, and results discussion. Section 6 concludes the study and points further research directions.

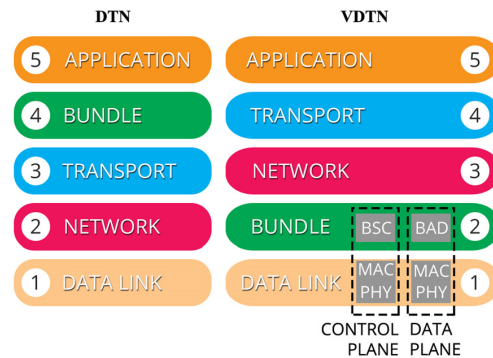


Fig. 1. Comparison between DTN and VDTN network architectures focusing on the bundle layer position.

2. Vehicular delay-tolerant networks

Vehicular Delay-Tolerant Network (VDTN) architecture [13] were created to overcome some of the above-presented issues faced by vehicular networks. They offer support for a wide range of applications and scenarios characterized by asynchronous and delay tolerant communications that do not need an end-to-end connectivity and accept some data loss. To support this type of environments, the VDTN architecture gathers several important contributions from others architectures, such as Delay Tolerant Networking (DTNs) [12], allowing to implement a store-carry-and-forward overlay network with a bundle oriented communication. Fig. 1 illustrates a comparison between the DTN and VDTN architectures. The VDTN architecture presents several improvements when compared to the DTN approach. By placing the bundle layer between the data link and network layers it manages to aggregate large amounts of IP datagrams sharing the same characteristics (e.g., destination node, application, and quality of service – QoS) into bundles. This approach allows reducing the complexity and packets processing of routing decisions, which is crucial in networks with energy constraints since this it results in significant energy savings [18].

In VDTNs, nodes communicate with each other considering two distinct planes: control and data. To allow this implementation, the bundle layer is divided into two sub-layers: the bundle signaling control (BSC) and the bundle aggregation and de-aggregation (BAD). The BSC executes the control plane functions (e.g., node discovery and routing), which based their operation on the signaling information exchanged between nodes at each contact opportunity through a separate and dedicated low-power link. This link is always active seeking for contact opportunities. The same information is also considered to set up, maintain, and terminate data plane connections. The BAD sub-layer is responsible to perform data plane functions (e.g., scheduling and dropping). Contrary to the control plane, the data plane uses a high-power link with short range that is only active if nodes have data bundles to exchange or during the estimated time calculated for a contact opportunity.

The VDTN architecture considers three different kinds of network nodes: terminal, relay, and mobile nodes. These nodes have different roles: terminal nodes act as access points to the VDTN network and may be responsible to perform traffic source and traffic sink functions; Relay nodes are fixed devices with huge storage capacity allowing mobile nodes to store and pickup data bundles. Moreover, this kind of node are usually placed at the most important road intersections aiming to improve the number of contact opportunities, which consequently improves the overall network performance [19]. Mobile nodes move along paths seeking for contact opportunities in order to disseminate data bundles across the

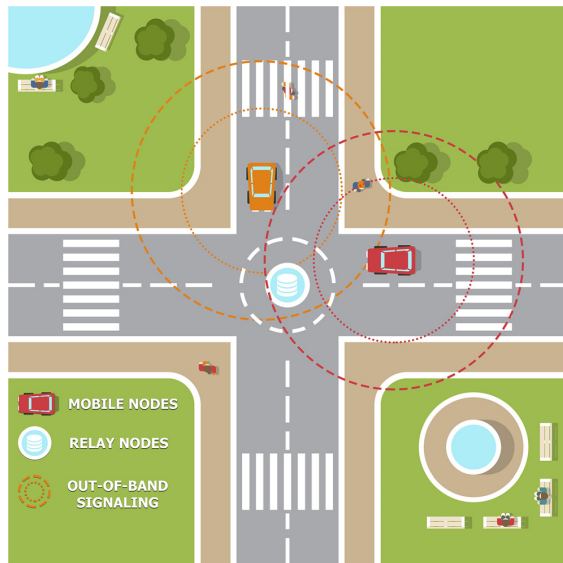


Fig. 2. Illustration of several conceptual characteristics of the VDTN architecture: i) three different kinds of VDTN network nodes; ii) interactions among network nodes; and iii) out-of-band signaling with the separation between the control and data planes.

network. Fig. 2 shows some of the above-presented concepts of the VDTN architecture.

3. Resources management in vehicular networks

The current maturity state of vehicular architectures instigates the proposal of innovative applications and services. To be effective on the network, new proposals must consider the single characteristics of vehicular networks, like sparse communications, latency, and resources limitations. Indeed, one of the major issues faced by vehicular networks is related with resources limitations. For this reason, is crucial to perform resources management functionalities. However, this is not an easy task since the highly dynamic topology and limited storage capabilities of vehicular network devices raise several challenges, which can lead to resource transmission failures or data loss, resulting on bandwidth and memory wasting. This section is devoted to present several approaches to deal with resources limitations that can be used as a starting point to propose new and better approaches.

Arshad et al. [20] proposed a semi-Markov model to deal with buffer management in wireless sensor vehicular networks. This model divides nodes buffer into states according to the occupancy percentage. With this approach, it is possible to solve the problem of data carrying between sensors and sinks. In this model, each sensor buffer has an occupancy constraint allowing dropping data packets only in case of saturation. In [21], a cloud computing architecture was proposed allowing vehicles to use it for sharing computation, storage, and bandwidth resources. This architecture is composed by three components: vehicular cloud, roadside cloud, and central cloud. Vehicular cloud is used to enable mobile nodes cooperation and communications among each other. Roadside cloud uses several roadside units to create a local cloud server allowing mobile nodes to have access to network resources. The central cloud is set through a group of dedicated servers across the Internet. To balance nodes resource competition, the proposed architecture takes advantages of a game-theoretical framework. A resource management scheme is proposed in [22]. This scheme aims to help on the handover decision process by performing an

access network selection through a reinforcement-learning algorithm that considers a semi-Markov Decision Process formulation. With this approach, this scheme minimizes the blocking probability maximizing the global system throughput. Cordeschi et al. [23, 24] proposed a resource management controller capable to adapt its operation taking into account the energetic and computational limitations of mobile nodes. It deals with this kind of limitations by dynamically control roadside units' access time-windows as well as the access rates and traffic flows. In [25], another resource management scheme is proposed taking advantages of a cooperative approach to overcome some bandwidth and resource-sharing problems. This cooperative approach introduces in service providers a coalition game model based on two-sided matching theory. This approach manages to improve the quality of service (QoS) for users and reduce the amount of consumed resources. A Fuzzy Logic based Resource Management scheme (FLRM) [26] was proposed to address the problem of resources presentation failures raised by the transmission of invalid data fragments. To prevent such situations to occur, this scheme collects and stores the request and download time of each resource. Then, based on this information, the survival time for each stored resource is calculated by a popularity evaluation algorithm allowing servers to update the resources list in real time. Arani et al. [27] proposed an energy-efficient resource management tool to perform in self-organizing heterogeneous networks like vehicular networks. This tool aims to overcome energy consumption and channel degradation problems in scenarios with heavy deployment of base stations. To perform such task, it considers several self-organizing mechanisms that take care of joint channels and power allocation procedures. Authors also proposed a dynamic allocation mechanism where the problem is defined as a non-cooperative game that it solved considering a no-regret learning algorithm. In [28], an efficient resource search and management scheme was proposed to enable management functionalities without the need of a roadside infrastructure. This is achieved by a peer-to-peer protocol, called SMART, that is able to discover and manage resources in vehicular environments, which allows vehicles to organize themselves creating connections with each other to manage and share resources. A resource management scheme based on message criteria for vehicular networks were proposed in [29]. This scheme introduces a method where vehicles are stored in memory until an overflow occurs. Therefore, an efficient memory management method is modeled and enforced in the network to improve the overall network performance. Other approaches [30–34] focus on exploring new resource allocation approaches to manage and optimize the consumption of network resources. A mathematical framework [32] stands out from these proposals by considering contacts duration to perform resource allocation tasks. To perform such task, it takes into consideration the unique characteristics of network architectures with opportunistic communications to better handle offloading decisions aiming to optimize available resources to support mobile data traffics. In [34], the authors enumerate the most tough and challenging issues in the resource management topic, which dynamic vehicular networks need to overcome. In this work the potentials of software-defined for vehicular networks are discussed, as well as the need to rethink the traditional software defined networking paradigm when applied to a resource management context.

All these proposals do not fit within the unique characteristics of VDTNs. For example, they are not design to operate and take advantages of the out-of-band signaling methodology, which has a huge impact on power savings and resources consumption. To the best of our knowledge, there is not a resource management methodology or tool for VDTNs that takes into consideration the specific characteristics of the VDTN architecture. Thus, the proposal of REMA tries to fill this gap.

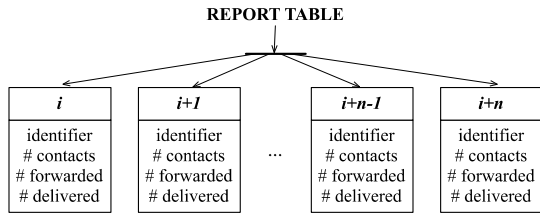


Fig. 3. Illustration of the report table maintained by network nodes allowing REMA operation.

4. Resource Management (REMA) tool

This section is devoted to describe the main principles and operation of REMA, a new tool designed to deal with resources management in VDTNs. This tool takes advantages of the VDTN out-of-band signaling and the store-carry-and-forward paradigm to assist routing protocols not only in the forwarding decisions but also in resource management tasks. REMA is intended to operate in scenarios where it is very important to have an accurate bundle delivery mechanism or where routing protocols cannot contain the amount of wasted resources (e.g., urban scenarios with significant number of copies of each bundle). Next sub-section describes the operation of REMA tool.

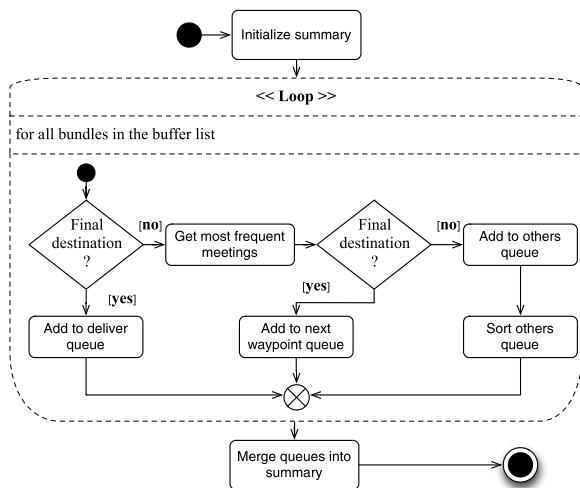
4.1. REMA operation

The VDTN architecture introduced an out-of-band-signaling approach, with the separation of control and data planes. REMA takes advantages of such approach to create an accurate scheduling methodology intending to delivery more bundles to the final destination with the less possible effort. To accomplish such task, at the beginning of the network operation, nodes are asked to maintain a report table (Fig. 3) containing crucial information about the contact opportunities they participated. For example, for each table entry, nodes will store the node unique identifier, the number

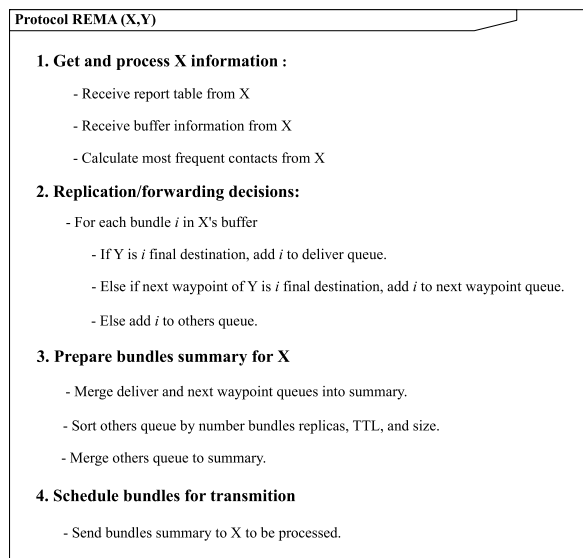
of contacts with such node, the number of forwarded bundles, and the number of delivered bundles.

This information will allow REMA to calculate which are the best nodes options to receive a bundle in order to deliver it to its final destination. Then, at each contact opportunity, when nodes are performing the control plane, REMA asks them to share their report tables, stored bundles summary, and also the next waypoint of their routes. Based on this information REMA calculates and suggests which bundles can be forwarded at the data plane. To perform such task, REMA creates and orders a summary list of bundles based on a set of parameters (Fig. 4a and 4b). Bundles which destination is the next waypoint of participating nodes are scheduled first. Afterwards, REMA calculates which destinations are commonly meet by the next waypoint of both participating nodes. Bundles which final destination is one of these nodes are scheduled next. Then, bundles are scheduled taking into consideration the following parameters: number of bundle replicas, bundles time-to-live (TTL), and bundles size. When REMA finishes the above-presented process, it sends to both nodes a summary report that nodes will use to replicate bundles at the data plane. This approach will allow REMA to balance the number of copies per bundle, preventing to have high discrepancies between the most and less replicated bundles. It also intends to give all bundles the same probability to reach their final destination.

REMA operation is not limited to calculate the best bundles to forward/replicate. It also operates when a buffer constraint is detected. Usually, this means that a node to continue receiving bundles from others must drop one or more bundles from its buffer. This can severely comprise the changes of certain bundles to reach their final destination. For example, dropping a bundle copy with a lower replication rate may mean that this copy is the last replica of the original bundle in the network, which will comprise the changes of delivering it. To minimize this situation, when a buffer constraint is detected in a node's buffer, REMA is asked to calculate which bundles should be dropped. To perform such task, it sorts the buffer's bundle list taking into consideration the following parameters: remaining TTL, number of bundles replicas, time in



(a)



(b)

Fig. 4. (a) Illustration of REMA's process to calculate which bundles should be replicated and (b) REMA double-step scheduling approach represented in pseudo-code.

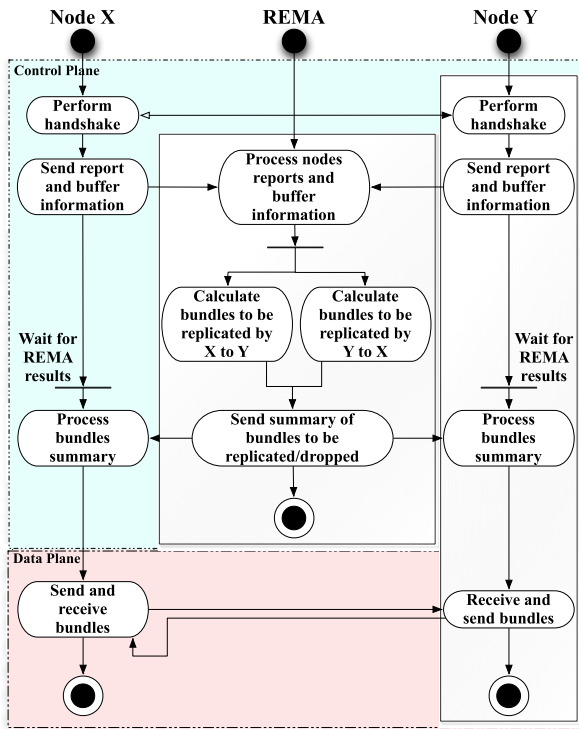


Fig. 5. UML activity diagram describing the sequence of main actions executed in REMA when two nodes exchange data among them.

buffer, and size. After this operation, bundles start to be dropped by the head of the list. Figs. 5 resumes the overall operation performed by REMA at each contact opportunity.

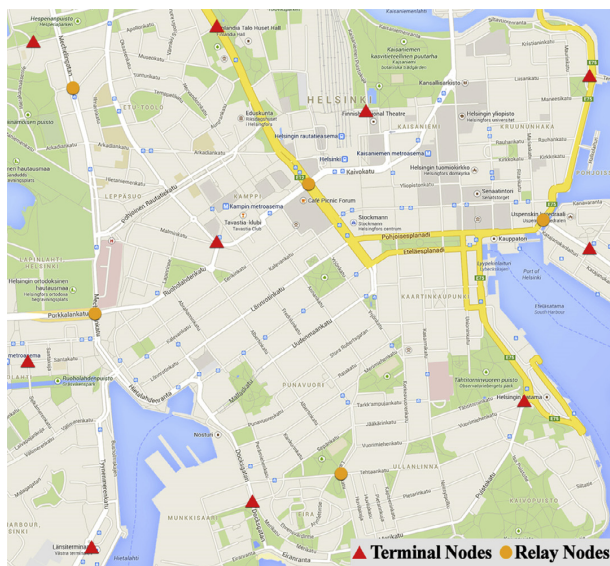
5. Performance evaluation

This section analyzes the performance of the proposed tool for VDTNs. To perform the simulation experiments VDTNsim tool [35] was considered. This simulation tool is an extension of the Opportunistic Network Environment (ONE) simulator [36] that adds support to the layered architecture model proposed by the VDTN architecture [37]. Next subsections present the simulation scenarios, the performance metrics considered in this study, and the corresponding results analysis.

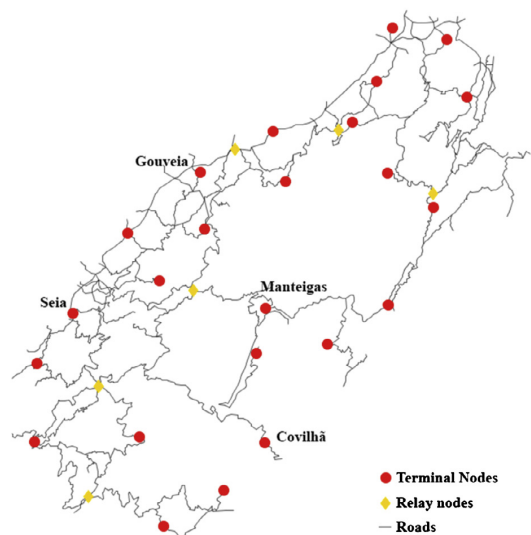
5.1. Simulation setup

To evaluate the efficiency of the proposed scheme two kinds of scenarios were set up, representing both urban and rural environments. The urban scenario considers a map-based model representation of a downtown part of the Helsinki city (Fig. 6a). In this scenario, 10 terminal nodes, each one with 100 megabytes (MB) of buffer capacity, are placed at the map positions represented in Fig. 6a. During a period of 12 h (e.g., from 12:00 to 24:00), 100 mobile nodes with 50 MB of buffer move along map roads with an average speed of 50 km/h. They are configured to act as traffic sources by generating data bundles to be delivered to random terminal nodes (i.e., traffic sinks). Each bundle is generated assuming an inter-bundle creation interval time in the range of [30, 60] seconds and with sizes uniformly distributed in the ranges of [25 KB, 100 KB], [250 KB, 500 KB], and [750 KB, 1 MB] (Bytes), respectively. Five relay nodes were placed at the most important crossroads aiming to increase the number of contact opportunities [19]. Each relay node has a buffer capacity of 200 MB. In this scenario, mobile nodes

For the rural scenario (Fig. 6b), 24 terminal nodes with 250 MB of buffer capacity were placed at real-world sparse locations. Due to the low density of mobile nodes, in this scenario, 6 relay nodes were deployed with 500 MB of buffer capacity to store a larger number of bundles. Bundles are transported between terminal nodes by 40 mobiles nodes, which move along roads with a buffer capacity of 125 MB and a velocity in the range of 30 to 80 km/h.



(a)



(b)

Fig. 6. Simulation scenarios with the location of terminal and relay nodes representing: (a) a small part of the Helsinki city (Finland); and (b) Serra da Estrela region.

Table 1
Summary of the configuration parameters for both considered scenarios.

Setting	Scenario	
	Helsinki	Serra da Estrela
Terminal Nodes (TN)	10	24
TN Buffer Capacity	100 MB	250 MB
Relay Nodes (RN)	5	6
RN Buffer Capacity	200 MB	500 MB
Mobile Nodes (MN)	100	40
MN Buffer Capacity	50 MB	125 MB
MN speeds	50 km/h	[30, 80] km/h
Bundle Size	[25 KB, 1 MB]	[500 KB, 2 MB]
Bundle TTL	[120, 360] minutes	
Bundle creation interval	[30, 60] seconds	[15, 30] minutes
Spray and Wait number of copies	15	6

To assess the performance of REMA under different conditions and constraints, in this scenario terminal nodes are responsible to generate bundles, with a creation time interval in the range of [15, 30] minutes, and with a size ranging from 500 KB to 2 MB. They also act as traffic sink since they are bundles final destination.

Across performance simulations, data bundles time-to-live (TTL) changes between 120, 180, 240, 300, and 360 minutes. As suggested in [38], to increase the realism of protocol simulations, all network nodes have a omni-directional transmission range of 30 meters and a transmission data rate of 4.5 Mbps. Epidemic [15], Spray and Wait [16], and GeoSpray [17] protocols were chosen as underlying routing schemes. For the Spray and Wait routing protocol, the binary version was considered and the number of copies parameter (L) is set to 15 in the urban scenario and to 6 in the rural scenario. These values for L were chosen based on the study presented in [39] that suggests that the number of copies should be equal to 15% of the number of mobile nodes available in the simulation scenario. Each simulation scenario was executed 30 times using different random seeds, which allows getting representative and meaningful results. Table 1 summarizes the parameters considered for both scenarios.

5.2. Performance metrics

To evaluate the performance of the routing schemes considered in this study, the bundle delivery probability and the average bundle delivery delay was set as the main performance metrics. The bundle delivery probability (B_{DP}), presented in Equation (1), is calculated as the relation between the number of unique bundles that are delivered to the final destination (D_{UB}) and the number of created bundles (C_B). The bundle average delivery delay (B_{ADD}) is measured as the average period of time that bundles need to travel from source to destination. It is calculated according to Equation (2), where B_{Dt} is the time when a bundle is delivered, while B_{Dt} is the time when the delivered bundle was created.

To better understanding the impact of the proposed tool on the performance of routing protocols regarding resources consumption the protocol overhead ratio (P_{OR}), which measures the number of “extra” bundles needed for each bundle to be delivered, and the number of dropped bundles were also studied. The protocol overhead ratio is calculated according to Equation (3), where T_B is the total number of successfully transmitted bundles.

$$B_{DP} = \frac{D_{UB}}{C_B} \quad (1)$$

$$B_{ADD} = \frac{\sum_{i=1}^{D_{UB}} (B_{Dt} - B_{Ct})}{D_{UB}} \quad (2)$$

$$P_{OR} = \frac{T_B - D_{UB}}{D_{UB}} \quad (3)$$

5.3. Performance analysis of REMA deployed on Helsinki scenario

The performance analysis starts with the behavior analysis of the considered routing protocols in terms of bundle delivery probability and bundle average delivery delay with and without the proposed resource management tool. As may be seen in Fig. 7a, REMA manages to improve routing protocols performance allowing them to deliver more bundles when compared to their traditional approaches. This is caused by an improved scheduling methodology, which considers a two-step forward approach that only forwards a bundle to nodes able to directly delivery or that have a high probability to meet its final destination. Epidemic with REMA manages to deliver more 4%, 9%, 7%, 8%, and 6% of bundles for each considered values of bundle TTL. Regarding Spray and Wait, with the proposed resource management tool it manages to deliver more 10%, 11%, 13%, 12%, and 10% of bundles for a bundle TTL equals to 120, 180, 240, 300, and 360 minutes, respectively. GeoSpray has a similar behavior delivering more 7%, 8%, 8%, 9%, and 11% of bundles. As expected, the scheduling methodology of the REMA will retain bundles in nodes buffer for a large period of time, which will consequently increase the bundle average delivery delay. This is demonstrated in Fig. 7b. However, and as may be confirmed by the significant increase of the delivery ratio, such situation does not have consequences for the network performance.

Now, the study focuses on the performance comparison considering the protocol overhead ratio and the number of dropped bundles. As may be seen in Fig. 7c and Fig. 7d, REMA has a significant impact in protocols that do not limit the number of copies by each bundle. For example, Epidemic running with REMA needs, in average, less 199, 445, 556, 620, and 700 “extra” bundles replication to deliver a bundle to its final destination and drops less 799149, 698732, 669609, 609975, and 567298 bundles (for a bundle TTL equals to 120, 180, 240, 300, and 360 minutes, respectively). This is achieved by the sophisticated two-step forwarding methodology, that considers nodes next contact opportunity prediction to reduce the number of unnecessary bundles transmissions contributing to less bundle replications and consequently to a significant decrease of the number of dropped bundles.

Although the impact of REMA on Spray and Wait and GeoSpray, in terms overhead ratio and dropped bundles is lower than on Epidemic, it still contributes to improve their performance in both metrics when compared to their traditional approach. This is due to the bundle copy limitation imposed by both protocols. Regarding Spray and Wait performing with REMA, it needs (in average) less 2, 2, 2, 2, and 1 “extra” bundle (for a bundle TTL equals to 120, 180, 240, 300, and 360 minutes, respectively) and drops less 429, 4979, 7952, 8651, and 8405 bundles when compared to its traditional approach. The performance of GeoSpray is very similar to Spray and Wait in terms of overhead ratio. In terms of dropped bundles REMA enforced on GeoSpray manages to drop less 3216, 5264, 6927, 7960, and 8789 bundles when compared to its traditional approach.

5.4. Performance analysis of REMA deployed on Serra da Estrela scenario

This scenario is a representation of a rural environment, which allows REMA to be deployed and its performance evaluated in an environment characterized with sparse contact opportunities and low node density (see Fig. 8). Following the same result analysis of the above-presented scenario, this study starts with the obtained results for the bundle delivery probability. REMA manages to help routing protocols to deliver more bundles to their final destination, when compared to the common approach where they are responsible to deal with resources management. Epidemic with REMA manages to deliver more 1%, 2%, 3%, 4%, and 11% of bundles for

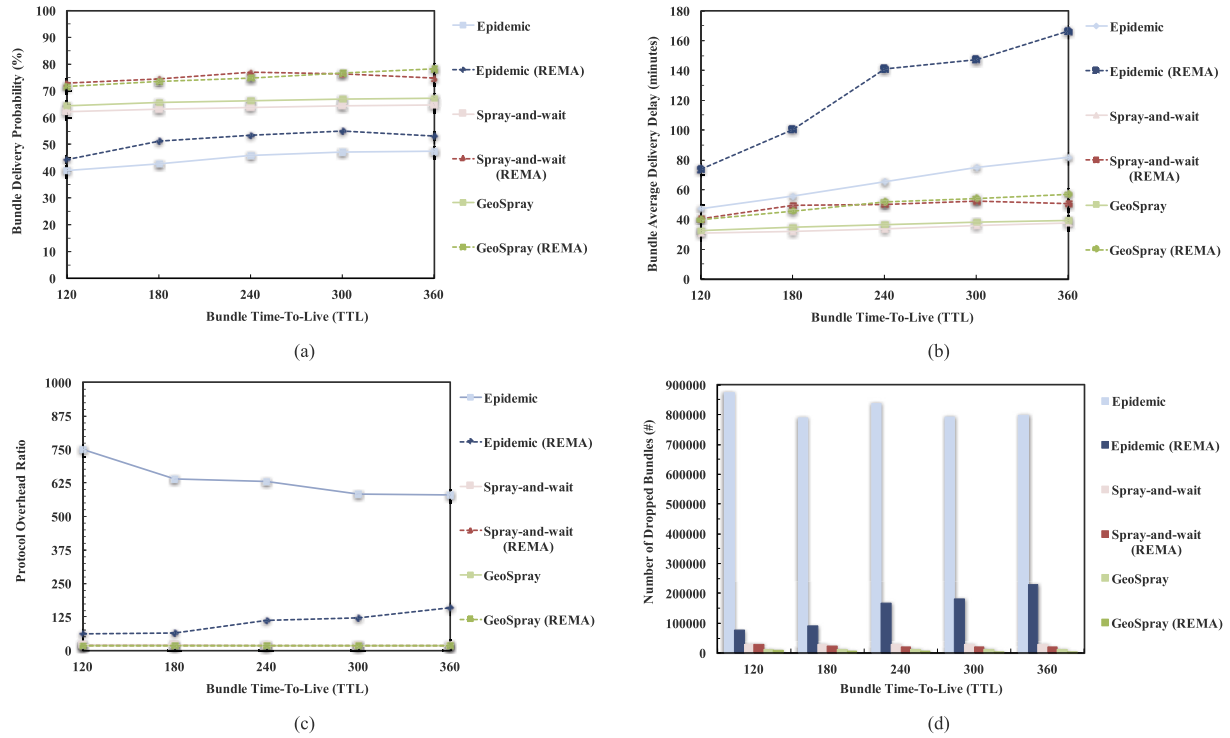


Fig. 7. Performance results for (a) Bundle delivery probability; (b) Bundle average delivery delay; (c) Overhead ratio; (d) Number of dropped bundles as function of bundles TTL for Epidemic, Spray and Wait, and GeoSpray routing protocols with and without REMA, when the Helsinki scenario is considered.

a bundle TTL equals to 120, 180, 240, 300, and 360 minutes, respectively. Regarding Spray and Wait, with the proposed resource management tool it manages to deliver more 1%, 3%, 3%, 3%, and 4% of bundles for the TTL values under study. GeoSpray has a similar behavior delivering more 1%, 6%, 7%, 6%, and 8% of bundles. As may be seen, REMA performance has less expression when bundles TTL is equal to 120 minutes. In this specific scenario bundles are dropped mostly by TTL expiration, which is explained by the sporadic contact opportunities and low node density that characterized rural environments. Regarding the bundle average delivery delay, in this scenario REMA follows the expected behavior, increasing the time bundles need to travel between source and destination nodes.

Now the study focuses on the amount of wasted resources. REMA proves to be effective in decreasing the amount of dropped bundles and the protocol overhead ratio. Although its efficiency in protocols that limits the number of copies of each bundle (e.g., Spray and Wait and GeoSpray), the impact of REMA is more evident when enforced in Epidemic. It manages to drop less 558, 36825, 95021, 143154, and 178347 bundles when compared to its traditional approach. Regarding the protocol overhead ratio, with REMA, Epidemic needs less 17, 572, 1569, 2286, and 2931 “extra” bundles (for the considered range of TTL values) to deliver bundles to their final destination.

5.5. Discussion

The effective operation of the proposed scheme relies on a double step scheduling methodology capable to predict and estimate nodes next contact opportunity to forward bundles in the best interest of the network. This approach is focused on preventing nodes from wasting resources that are essential for the proper functioning of the network, since it prevents unnecessary

bundles to be forwarded to nodes that aren't or have lower probability to meet their final destination. As a consequence, bundles will be retained in nodes buffers for a longer period of time, which will increase the bundle average delivery delay. In scenarios with lower bundle TTL this could affect the bundle delivery probability, since bundle will be dropped mainly due to TTL expiration. By the other hand, REMA is capable to significantly decrease the number of buffer constraint situations, which make nodes more receptive to share resources with others. Thus, REMA is also capable to control the flooding methodology of routing protocols that do not limit the number of copies per bundle managing to deliver more bundles with less network effort. It also decreases the number of bundle replications needed to deliver bundles to their final destination. This approach contributes to decrease the power consumption, which is a very important achievement in networks with resources constraints.

6. Conclusion and future work

This contribution proposed a resource management tool for VDTNs, called REMA. To be deployed in the VDTN architecture, REMA must handle several important constraints. The absence of an end-to-end path, the highly dynamic network topology, and short and sparse contact opportunities are examples of constraints faced by the VDTN architecture.

REMA was designed to operate in challenging environments characterized by high resources constraints. It takes advantages of the VDTN store-carry-and-forward paradigm and the out-of-band signaling to introduce an accurate double-step scheduling mechanism that is capable to estimate nodes next contact opportunity forwarding bundles in the best interest of the network. First, it starts to ask network nodes to maintain a report table containing all the information about the contact opportunities they have with

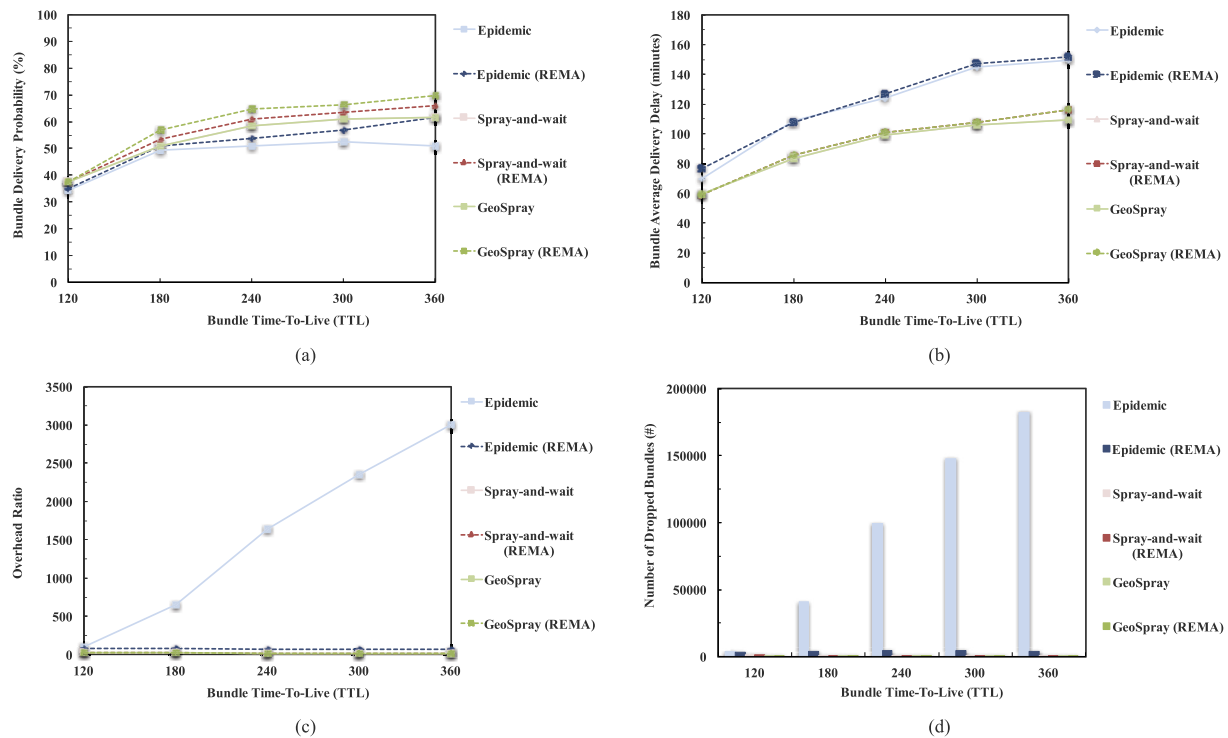


Fig. 8. Performance results for (a) Bundle delivery probability; (b) Bundle average delivery delay; (c) Overhead ratio; (d) Number of dropped bundles as function of bundles TTL for Epidemic, Spray and Wait, and GeoSpray routing protocols with and without REMA, when the Serra da Estrela scenario is considered.

others. Then, at each contact opportunity, nodes send to REMA their contact reports and which bundles they are carrying in their buffers. This information is processed by REMA resulting on a bundles summary that is sent to nodes. After receiving REMA bundles summary, nodes begin the data plane process forwarding/replicating bundles to each other.

The performance evaluation of REMA was achieved in comparison with scenarios where no additional tool is considered to performed resource management functionalities besides those that are performed by routing protocols. Conducted studies considered as performance metrics the bundles delivery probability, the bundles average delivery delay, the protocol overhead ratio, and the number of dropped bundles. It was shown that REMA contributes to improve the overall network performance by delivering more bundles to the final destination and decreasing the amount of resources needed to deliver them. This is confirmed by the lower rate of dropped bundles and overhead ratio presented by REMA when compared to the traditional approaches followed by routing protocols.

Obtained results show that REMA manages balance network bundle flows and nodes resources without the need of a roadside infrastructure, which is a very significant finding in highly dynamic topology environments. Balancing bundle flows allows to decrease the number of buffer constraints, which consequently decreases the probability of nodes diverge from the protocol to save resources and keep their data integrity. This important finding increases nodes receptivity and confidence to share their resources with others allowing increasing the bundle delivery probability and, as a consequence, improving the overall network performance. Finally, by performing in both VDTN planes (control and data), REMA is capable to make accurate decisions regarding nodes and network interests based on real time information. Bundles are for-

warded or deleted taking into consideration the real state of network nodes at each contact opportunity.

As future work, experiments on REMA will be conducted taking into consideration a laboratory testbed for VDTNs, called VDTN@Lab [40]. This approach will allow evaluating the tool performance in a more realistic environment.

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Chapter 10

Conclusion and Future Work

Throughout this thesis, the performance assessment of vehicular delay-tolerant networks (VDTNs) was studied when performing together with cooperative, monitoring, and management strategies. This chapter presents the main conclusions that result from the research work performed on the 4-years length of this doctoral programme. Furthermore, it provides directions for further research topics.

10.1 Final Conclusions

After introducing and delimiting the focus and scope of the thesis, identifying the problem, describing the objectives, presenting the thesis hypothesis and its main contributions, in Chapter 2, the state of the art regarding cooperation in vehicular communications and delay-tolerant networking was reviewed and analyzed. This chapter began with an overview of vehicular ad hoc network architecture, applications, and services. After, several cooperative approaches for this architecture were analyzed and discussed, allowing presenting their limitations that motivated the introduction of new approaches and architectures. Concerning other architectures, the DTN and VDTN architectures were presented and discussed, as well as their contribution to the state of the art on cooperation. Several research topics were identified as open issues to be studied during this research work.

Chapter 3 presented the proposal of two levels of cooperation for VDTNs. Taking advantages of the VDTN out-of-band signaling, nodes are requested to cooperate in both planes. First, they must share a percentage of their buffer capacity to store bundles from others. Therefore, at the data plane, nodes must share a percentage of time at each contact opportunity to send bundles from others. Performance studies, considering five different routing protocols, concluded that by imposing cooperation in VDTNs it is possible to increase the network performance by delivering more bundles to their final destination. The observed results from this proposal motivated the introduction of four cooperative strategies, which were proposed, described, and analyzed in Chapter 4. All of them consider a cooperative value that is used by nodes to set the percentage of resources they must share with others. However, they distinguished from each other by the way this cooperative value is calculated. *Static Mandatory Cooperation (SMC)* strategy sets a fixed cooperative value at the beginning of the network operation, while *Random Mandatory Cooperation (RMC)* randomly calculates this value at each contact opportunity. Other two approaches (*Node Performance Cooperation and Inverse Node Performance Cooperation*) consider nodes performance across the network to set nodes cooperative value. Performance assessment shown that applying cooperative strategies in VDTNs is a reliable way to increase the overall network performance.

Previous studies considered a fully cooperative scenario. However, this scenario cannot be taken as granted. Due to resources constraints or a selfish behavior, nodes may diverge from

the protocol and be unwilling to cooperate. To deal with the presence of such kind of nodes three different approaches were proposed. First, a reputation system to detect, identify, and avoid communications with selfish nodes was presented in Chapter 5 and Appendix A. At the beginning of this system operation, nodes are assigned with a reputation score and create a reputation table. Each time a contact opportunity is available, the encountered node is added to the reputation table (if it does not already exist) and its reputation score is updated using the VDTN out-of-band-signaling at the control plane phase. Afterwards, the reputation system accepts or denies a contact opportunity based on the nodes' reputation score by comparing it with a network reputation threshold (α), which is equal to all the network nodes and is defined at the beginning of the system execution. Each time a node successfully delivers a bundle to its final destination, it is rewarded with an increase on its reputation score. On the other hand, each time a node drops a bundle without sending it at least once, it is punished and its reputation score decreases. Nodes performing with a reputation score lower than the network reputation threshold are marked as a selfish node and excluded from the network. Performance studies demonstrated the efficiency of the proposed system not only in dealing with misbehavior nodes but also in improving the overall network performance.

After, a hybrid system that proposed two incentive approaches (*Volume of Bytes Transferred* and *Time Spent to Cooperate*) to encourage selfish nodes to cooperate was proposed and its main features and performance evaluation are presented in Appendix B. Its operation is based on two modules: reputation and monitoring. The reputation module adapts the above-presented reputation system to communicate with the monitoring module. This will allow selfish nodes to be monitored instead of being excluded. The monitoring module tries to stimulate selfish nodes to cooperate by offering them rewards in exchange of their cooperation. In the case of selfish nodes, cooperation is measured by the volume of exchanged bytes and the time they spend forwarding bundles from others. Both metrics are used by the two proposed incentive approaches to reward/punish selfish nodes. Observed results confirm that by encouraging selfish nodes to share their own resources, helping others to deliver bundles, is a possible approach to reduce their negative impact on the network performance.

Lastly, the *Cooperative Watchdog System (CWS)* was described and analyzed in Chapter 6. This system was proposed to afford nodes with a tool able to detect selfish nodes. To perform such task, CWS assigns a reputation score to each network node. Thus, each time nodes participate in a contact opportunity, the CWS updates their reputation score based on the considerations of three modules (classification, neighbor's evaluation, and decision). The classification module aims to categorize nodes into different types, according to their reputation score. Founded on their categorization, the classification module calculates each node's cooperative value. The cooperative value is then transmitted to the decision module in order to punish or reward nodes in function of their cooperative behavior. The neighbor's evaluation module determines how neighbors evaluate a node's reputation on the network. This is accomplished by asking them their opinion about it. At the end of a contact opportunity, the decision module updates the nodes' reputation score based on the information transmitted by the other modules. Performance studies conducted through simulation (considering the bundle delivery probability, bundle average delay, overhead ratio, and number of dropped bundles) prove the effectiveness of this system in attenuate the impact of selfish nodes on the overall network performance. This is achieved by increasing the number of delivered bundles and decreasing the average time they need to travel from the source to the destination node. Furthermore, the

Conclusion and Future Work

CWS also succeeds on the resources waste reduction task, decreasing significantly the number of dropped bundles.

Chapter 7 concluded the research studies on the cooperation field by presenting an overview of the topic, providing motivations, challenges, and an evaluation of the impact of cooperative measures on the performance of VDTN networks.

Taking into account the particularities of the VDTN network architecture, monitoring and management strategies and methodologies were created to optimize the quality of service (QoS) of communications between network nodes. Although, and before implementing new approaches for this topic, a comprehensive review about the most relevant strategies already proposed to deal with monitoring and management issues in vehicular and delay-tolerant communications was conducted and presented in Chapter 8. It started by identify and describe the most relevant challenges and network functionalities regarding vehicular environments. Then, a detailed review of the state of the art considering the most relevant contributions on the monitoring and management research field regarding wireless and vehicular networks was performed. Finally, a discussion on network management and monitoring techniques for vehicular networks was performed, pointing several open issues that will facilitate further contributions.

The proposal and description of a monitoring and management tool for VDTNs, called *MoM*, which operates in real-time aiming to improve the overall network performance, is presented in Appendix C. This tool intends to decrease the impact of resource constraint nodes in the network by affording VDTNs with a sophisticated tool that can rapidly and accurately detect network anomalies and constraints. *MoM* takes advantages of the VDTN architectural approach to collect statistical information about the performance of each network node and to spread across the network measures to held constraint nodes or instructions for network nodes to take some kind of action against nodes responsible for decreasing the network performance. To perform both monitoring and management functions, this tool considers three modules: monitoring, management, and user interface. The monitoring module is responsible to process mobile nodes reports and to keep updated a network state table containing all relevant information about each network node. The management module is responsible to generate network advertisements when it is notified by the monitor module. These advertisements are generated aiming to inform nodes about a behavior they must adopt or an action they must have against others. Finally, the user interface module is used to display to network administrators the state of the monitored VDTN. Performance studies showed that *MoM* tool manages to achieve a better network performance when compared to an approach where no monitoring and management approach is considered.

Chapter 9 presented the last contribution of this thesis. It consisted on the implementation and description of a resource management tool, called *REMA*, which aims to help routing protocols to minimize the consumption of network resources contributing to increase the overall network performance. This is achieved by a sophisticated scheduling methodology that forwards bundles considering the best interests of the VDTN network. It was designed to operate in challenging environments characterized by high resources constraints. It takes advantages of the VDTN store-carry-and-forward paradigm and the out-of-band signaling to introduce an accurate double-step scheduling mechanism. First, it starts to ask network nodes to maintain a report table containing all the information about the contact opportunities they have with others. Then,

at each contact opportunity, nodes send to *REMA* their contact reports and which bundles they are carrying in their buffers. This information is processed by *REMA* resulting on a bundles summary that is sent to nodes. After receiving *REMA* bundles summary, nodes begin the data plane process forwarding/replicating bundles to each other. Conducted studies shown the applicability of *REMA* in VDTNs due to its influence on improving the overall network performance by delivering more bundles to the final destination and decreasing the amount of resources needed to deliver them. This was confirmed by the lower rate of dropped bundles and overhead ratio presented by *REMA* when compared to the traditional approaches followed by routing protocols.

The main objective of this thesis was the proposal of strategies and methodologies to increase the overall performance of VDTNs by addressing the most relevant challenges and open issues regarding cooperation, monitoring, and management fields. The main objective was fully accomplished, as well as the defined partial objectives. Cooperative challenges and open issues were addressed through the proposal of cooperative strategies. The VDTN operation was also adapted to support two distinct levels of cooperation. To deal with misbehavior nodes three system were proposed: a reputation system, a hybrid system to incentive selfish nodes to cooperate, and a cooperative watchdog system. Regarding network monitoring and management, a monitoring tool was designed to collect real-time information aiming to detect and held constraint nodes. To deal with resource constraints, a management tool was proposed. Conducted studies in both fields demonstrate that all the proposed strategies and methodologies managed to increase the overall network performance. Overall, the findings presented in this thesis provide a number of contributions that are believed to be relevant to the development of future architectures, services and applications to deal with the challenges of vehicular environments, mainly, based for VDTNs.

10.2 Future Work

To conclude this thesis and as a result of the investigations conducted during this doctoral programme, several research directions may be suggested aiming to guide further research studies on VDTNs:

- To propose, deploy, and evaluate mechanisms to deal with the highly dynamic topology and nodes mobility on VDTN networks.
- To propose, deploy, and evaluate mechanisms to deal with the traffic management on VDTN networks.
- To study, deploy, and evaluate security mechanisms in communication between network nodes preventing data integrity from being comprised.
- To introduce the concept of vehicular cloud networking in the VDTN architecture and evaluate its applicability through the VDTNSim [1] tool and the VDTN@Lab [2] laboratory testbed.
- To create and evaluate the performance of the proposals presented in this thesis in a real-world testbed [3], to compare with the results obtained by simulation.

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Appendix A

A Reputation System to Identify and Isolate Selfish Nodes in Vehicular Delay-Tolerant Networks

This appendix is based on the following paper:

A Reputation System to Identify and Isolate Selfish Nodes in Vehicular Delay-Tolerant Networks

João A. F. F. Dias, Joel J. P. C. Rodrigues, Lei Shu, and Sana Ullah

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A Reputation System to Identify and Isolate Selfish Nodes in Vehicular Delay-Tolerant Networks

João A. Dias¹, Joel J. P. C. Rodrigues¹, Lei Shu² and Sana Ullah³

¹Instituto de Telecomunicações, University of Beira Interior, Portugal

²Guangdong University of Petrochemical Technology, China

³King Saud University, Riyadh, Saudi Arabia

joao.dias@it.ubi.pt; joeljr@ieee.org; lei.shu@lab.gdpt.edu.cn; sullah@ksu.edu.sa

Abstract— Vehicular Delay-Tolerant Networks (VDTNs) were proposed as a solution to overcome some issues found in other vehicular technologies. VDTNs assume the bundle layer placement under the network layer. This vehicular architecture can be applied in sparse regions characterized by sparse connectivity, long propagation delays, high error rates, and short contact durations. Although some of the major issues were already solved and several improvements were already achieved, VDTNs still have several issues that should be overcome. One of these issues is related with nodes cooperation and nodes share their own resources to deliver packets from others. This can be a difficult task if selfish nodes affect the performance of cooperative nodes. To detect, identify, and avoid communications with selfish nodes, this paper proposes a reputation system with four different reputation mechanisms and studies their impact on the performance of the network. This reputation system is enforced on two different routing protocols (Spray-and-Wait and GeoSpray). Across all the experiments, it was shown that reputation mechanisms that punish aggressively selfish nodes contribute to an increase of the overall network performance by increase the number of delivery messages and decrease the message average delivery delay.

Keywords— Vehicular Delay-Tolerant Networks; Cooperation; Reputation System; Selfish Nodes; Performance Evaluation

I. INTRODUCTION

Vehicular Delay-Tolerant Networks (VDTNs) [1] are a subset of vehicular networks where a diversity of mobile and fixed nodes freely interact among them. To support communications VDTNs propose an architecture based on three design principles: *i*) an Internet Protocol (IP) over VDTN approach; *ii*) an end-to-end, asynchronous, and variable-length bundle oriented communication; and *iii*) a separation between control and data planes performing out-of-band signaling.

VDTNs consider three types of nodes: terminal, relay, and mobile nodes. Terminal nodes are fixed nodes representing the access points to the VDTN network and may act as traffic source and traffic sinks. Stationary relay nodes with store-and-forward capabilities are placed at roads intersections and

interact with mobile nodes in order to improve the number of contact opportunities that contribute to an increase of the overall network performance [2].

VDTNs gather important contributions from other vehicular network architectures, such as Delay Tolerant Networks (DTNs) [3]. For example, it considers the DTN store-carry-and-forward routing protocol. This approach allows VDTNs to solve several problems caused by intermittency, disconnection and long delays. However it distinguishes itself from DTNs by introducing the bundle layer under the network layer. This approach origins the introduction of two logical planes (control plane and data plane). At the control plane nodes exchange signaling messages in order to reserve resources (to be used at the data plane) and perform several routing decisions. If there are any bundles to exchange, data plane is activated during the estimated contact duration time, and functions like data bundles aggregation/de-aggregation, queuing and scheduling, and traffic classification are performed. This approach is very important because it not only ensures the optimization of the available data plane resources (e.g., storage and bandwidth), but also allows power saving, which is very important for energy-constrained network nodes, such as stationary relay nodes [1, 4].

Although the already conducted studies, VDTNs still presents a large number of technical challenges that should be overcome. One of these open issues is cooperation between network nodes. Previous studies on this topic [5] show that enforcing cooperation in VDTNs is not an easy task. For example it is important to stimulate nodes to cooperate in order to create an optimal cooperative system that provide quality of service (QoS) to increase the overall network performance without comprising or deteriorating nodes data. One way to achieve this issue is to afford nodes with sophisticated schedulers. These schedulers should take into account that in a cooperative networks two types of nodes should be considered: selfish and cooperative. Selfish nodes are unwilling to cooperate and in most cases they receive bundles forwarded by other nodes to drop them immediately. This behavior contributes to a huge waste of network resources (e.g., power).

Contrary to selfish nodes, cooperative nodes share their own resources to store-and-forward bundles from others. However, the behavior of selfish nodes may affect their performance.

In order to study the impact of selfish nodes this paper proposes a reputation system for VDTNs that considers nodes reputation scores calculated through nodes performance. For example, each time nodes successfully deliver a bundle, their reputation increases. However, each time they drop a bundle without sent it at least once, their reputation decreases. This system considers four different ways to penalize nodes with a selfish behavior. All four approaches distinguish itself from others by the way they reward/penalize nodes by their behavior.

The main contributions of this paper are the following:

- A review of the state of the art considering the most relevant contributions on reputation systems for vehicular networks;
- Proposal of a reputation system for VDTNs with four different strategies to identify and avoid selfish nodes;
- Exhaustive studies to evaluate the network performance improvement considering the proposed reputation system on VDTN nodes, using the most relevant routing protocols;

The remainder of this paper is organized as follows. Section 2 focuses on the cooperation problem and presents a review of the state of art on cooperation and reputation systems in vehicular networks. Section 3 describes the proposed reputation system and how it can be enforced in VDTNs, whereas Section 4 presents the experimental settings and the performance assessment of the proposed reputation system in VDTNs. Finally, Section 5 concludes the paper providing a final summary of the study and points further research topics.

II. RELATED WORK

In vehicular environments cooperation among network nodes assume a key role in order to carry messages from source to destination. This dependence may be a huge problem when nodes are forced to diverge from the protocol to save their own data and resources. But nodes may also diverge from the protocol and be unwilling to cooperate due to a selfish behavior. Selfish nodes may belong to individual users that are not interested to share their own resources to forward messages from other users. In both situations, this selfish behavior severely affects the overall network performance.

To reduce the impact of selfish nodes, one possible solution is to create a reputation system that allows nodes to detect, identify, and avoid such nodes. Several approaches were already been proposed in the literature. For example, a reputation system to isolate selfish nodes in Ad Hoc networks is presented in [6]. This reputation system implements different reputation functions that allow nodes to autonomously evaluate the reputation of its neighbors based on the completion of the requested service. This study demonstrates the importance of choosing the way nodes are punished by their selfish behavior.

Dotzer *et al.* [7] propose a reputation system for VANETs [8] called VARS. This scheme assigns a reputation score to network nodes based on an opinion generation and confidence of the decision. Each time a node receives a message from others it generates an opinion based on the trustworthiness of this message. To calculate this opinion, nodes may consider partial opinions attached to the message, opinions from other nodes (if the sender is known), or a combination of both. Next time this message is forwarded, the new opinion is attached to it.

In [9] a long-term reputation system for vehicular networking is proposed. This system provides reliable reputation scores by taking advantages from nodes daily trajectories. Based on this experience, roadside infrastructure could rely on repeated daily observations of the same set of passing-by vehicles to build long-term reputation scores. To be deployed in a vehicular network this scheme only requires nodes to have a secret and verifiable certificate.

Anand Patwardhan *et al.* [10] propose a reputation management scheme to be applied in VANETs. To evaluate nodes reputation scores this scheme considers cooperativeness and accuracy of peer-provided data. To calculate this tokens the proposed scheme uses persistent identifies, frequency of encounters, and a know set of anchored trustworthy sources to serve as nucleating points for building trust relationships with a previously unknown devices. In addition this scheme implements an epidemic exchange protocol to ensure high reliability of data and stimulate proactive collaboration between nodes.

This section overviewed the most important contributions already proposed to deal with node reputation and selfish nodes in vehicular networks. They may be considered as a starting point to propose new ways of dealing with this problem in VDTNs.

III. REPUTATION SYSTEM

This section, divided into two sub-sections, focuses on the description of the proposed reputation system. The first sub-section overviews the reputation system focusing on the system operation mode, while the second sub-section describes the four reputation mechanisms implemented by the reputation system.

A. System Overview

The main goal of a reputation system in VDTNs is to provide a tool that allows nodes to identify and avoid contacts with selfish nodes, in order to optimize the overall network performance. To achieve such goal, each network node builds a reputation table containing all nodes that have been encounter by this, as well as a reputation score for each one of them. Each time a contact opportunity is available, the reputation score of the encountered node is updated using the VDTN out-of-band signaling at the connection setup phase. At this phase nodes exchange control information, such as node type, geographical location, route, speed, supported link technologies properties, energy status, and buffer status, among others. When the reputation system is active, nodes also exchange their reputation score.

After exchanging the control information, the reputation system accepts or rejects a contact based on nodes reputation score by comparing it with a reputation threshold (α) equal to all network nodes. If nodes reputation is higher than α then they are able exchange bundles. At the end of each contact, nodes reputation score is updated. To calculate nodes reputation score, the reputation system considers two variables: delivered bundles and dropped bundles. Each time a node successfully delivers a bundle to its final destination, the reputation of the forwarded node increase. By the other hand, each time a node drop a bundle without sent it at least one time, its reputation decrease. Each time a reputation node is below the threshold, the node is identified as a selfish node and is added to blacklist. Nodes represented in the blacklist are ignored. Figure 1 illustrates how the reputation system performs.

The reputation score is not only used to determine if a contact is accepted or reject, but is also used to set the cooperative threshold. For example, if a node has a reputation score equal to 60, it means that this node will reserve 60% of its buffer capacity to store bundles from other nodes. It also means that this node will spend 60% of an available contact time sending messages from other nodes. With this approach it is expected that selfish nodes will be identified and isolated soon in order to improve the overall network performance.

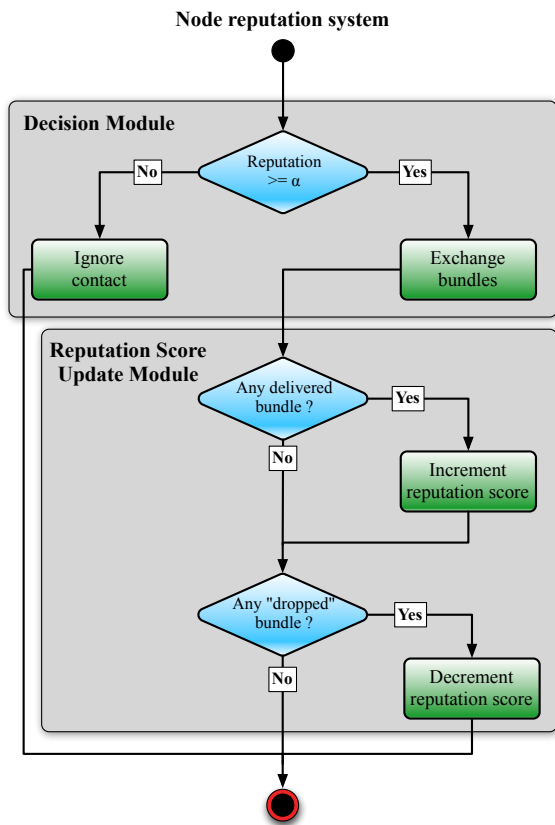


Fig. 1. Illustration of the VDTN reputation system workflow.

B. Reputation Mechanisms

The Reputation Score Update Module has four different heuristics to update nodes reputation score: Simple Increment Simple Decrement (*SISD*), Double Increment Simple Decrement (*DISD*), Simple Increment Double Decrement (*SIDD*), and Simple Increment Message Hop Decrement (*SIMHD*).

In the *SISD* heuristic, each time a node successfully delivers a bundle to its final destination, its reputation score increase k units, where k is a positive constant. By the other hand, each time a node drops a bundle without sent it at least once, its reputation score decrease k units. This scheme punishes nodes in the same proportion that reward them. The *DISD* and *SIDD* schemes are a variation from this first scheme. The main difference between them is how they reward/punish nodes. In the *DISD* scheme, nodes increase their reputation in $2k$ units each time a bundle is delivered to its final destination. Contrary to this, *SIDD* scheme punish nodes in $2k$ units each time a bundle is dropped without having been sent once. This scheme will allow to observe if it is most important to reward nodes or to punish them by their selfish behavior.

The *SIMHD* scheme considers the number of hops between bundle source and the node where the bundle is dropped (without been sent once) to punish nodes. This scheme is more aggressive than the other schemes in penalizing nodes by their selfish behavior. Each time a node drops a bundle without sent it once, its reputation score decreases $2k + h*k$, where h is the number of bundle hops between the source and the current node. The idea behind this scheme is to punish nodes by the effort of previous nodes to deliver bundles.

IV. PERFORMANCE EVALUATION

This section focuses on the performance analysis of the above-presented reputation system and its impact on the performance of VDTNs. Considering the reputation mechanisms presented at the end of the last section, simulation studies were conducted using the VDTNsim tool [11]. This tool is an extension of the ONE simulator [12, 13] and allows simulating the VDTN architectural approach, which comprehends the store-carry-and-forward overlay network below the network layer.

This section is divided into four subsections. The first one describes the network scenario, as well as all the parameters and performance metrics considered for all the conducted studies. The second subsection focuses on the performance of the Spray and Wait routing protocol [14], while the last subsection focuses on the performance of a VDTN routing protocol, called GeoSpray [15]. Both protocols were chosen because they were the best performing protocols in previous studies focused on cooperation in VDTNs [5]. Finally, the last subsection presents a discussion about the obtained results.

A. Network Scenario

The simulation scenario, shown in Figure 2, considers a map-based model representation of the *Dakar* region in Senegal, Africa. It is considered a simulation period of 24 hours, in cooperative opportunistic environment without knowledge of the traffic matrix and contact opportunities.

Twenty-seven real world clinics, represented in the same figure, were selected to place terminal nodes that act as traffic sources. Each traffic source node has a 125 MB (MegaBytes) buffer, and generates bundles using an inter-bundle creation interval in range [15, 30] minutes uniformly distributed random values. Each bundle has a size range [500 KB, 2MB] with uniformly distributed random values. All bundles exchanged in the simulations have an infinite time to live (TTL). Their destination address is the terminal node connected to the Internet that acts as the traffic sink.

A group of 100 vehicles (e.g., mobile nodes) moves along the map roads and each has a 50 MB buffer. When a vehicle reaches a terminal node, it randomly waits from 15 to 30 minutes. Then, it randomly selects its next destination node. Afterwards, a random speed between 30 and 80 km/h is selected, and the vehicle moves along the roads using the shortest available path. From these 100 mobile nodes, 25 will act as selfish nodes, receiving bundles from other nodes and dropping them immediately after that. The remaining 75 mobile nodes act as cooperative nodes, sharing their resources depending on their reputation score.

Seven relay nodes, each with a 250 MB buffer, are placed at the selected crossroads presented in Figure 2. All network nodes connect to each other using IEEE 802.11b with a data rate of 6 Mbps, and a transmission range of 350 meters using omni-directional antennas. This study evaluates the impact of selfish nodes in the overall performance of VDTNs and how the reputation system can help to identify and isolate them. Five different reputation thresholds (10, 20, 30, 40, and 50) were study along the simulation runs.



Fig. 2. Illustration of the Dakar region (Senegal) representing map roads and the location of terminal (clinics) and relay nodes.

Performance metrics considered in this study are the bundle delivery probability and the bundle average delivery delay. The bundle delivery probability (D_p) is defined as the ratio between the number of unique bundles (i.e., does not count bundle replicas) that have reached the final destination node(s) and the total number of unique bundles that was created at the source node(s). It is calculated according to Equation 1, where D_p is the bundle delivery probability, D_B is the total number of unique delivered bundles, and C_B is the total number of unique created bundles.

The bundle average delivery delay is defined as the average time between bundles creation and delivery. It is calculated according to Equation 2, where D_D is the bundle average delivery delay, Td_i is the time when the bundle i was delivered,

Tc_i is the time when the bundle i was created, and D_B is the total number of unique delivered bundles.

$$D_p = \frac{D_B}{C_B} \tag{1}$$

$$D_D = \frac{\sum_{i=1}^{D_B} (Td_i - Tc_i)}{D_B} \tag{2}$$

B. Performance Evaluation considering Spray and Wait routing protocol

The results observed in simulation experiments with Spray and Wait routing protocol, demonstrate the importance of introducing a reputation system to identify selfish nodes in the network. Figure 3 shows that all the considered reputation mechanisms helps to reduce the impact of selfish nodes by increasing the number of delivery bundles. The same figure also shows that mechanisms that are more aggressive to penalize selfish nodes (SIHMD and SIDD) outperform those who do not have this approach (SISD and DISD). More accurately, SIHMD presents gains of approximately 4%, 3%, and 2% (for cooperation threshold equals to 20, 30, and 40, respectively) when compared to the SISD reputation mechanism. When compared to the DISD mechanism, it presents gains of approximately 4%, 3%, and 2%. SIHMD and SIDD mechanisms have a very similar performance.

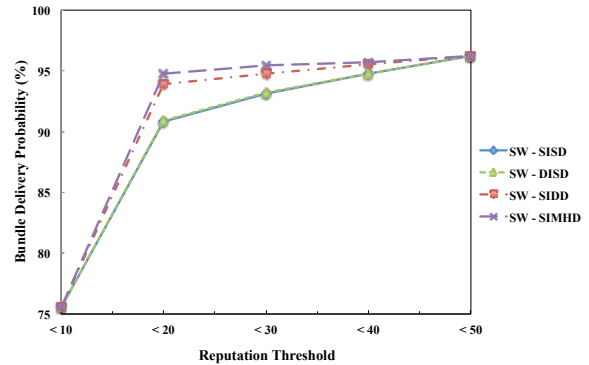


Fig. 3. Bundle delivery probability as function as reputation nodes threshold for Spray and Wait routing protocol, considering SISD, DISD, SIDD, and SIMHD reputation mechanisms.

Figure 4 confirms the results observed in Figure 3. Schemes that punish nodes in a more aggressive way not only deliver more bundles but also deliver bundles sooner. Comparatively with the SISD, the SIMHD scheme delivers bundles approximately 52, 67, and 28 seconds sooner (for cooperation threshold equals to 20, 30, and 40, respectively). When compared to the DISD, the same scheme delivers bundles 74, 75, and 34 seconds sooner. Despite SIMHD and SIDD have a very similar performance in terms of bundle deliver probability, in terms of bundle average delay the SIMHD delivers bundles 31, 14, and 12 seconds sooner.

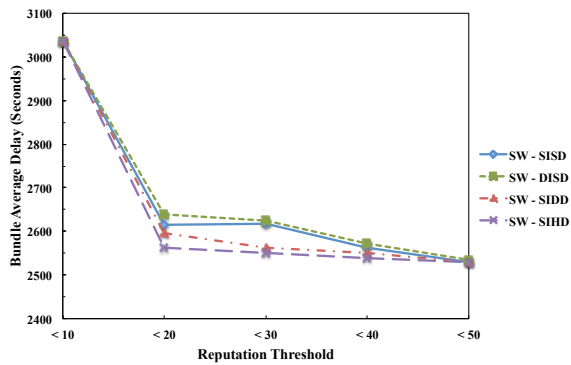


Fig. 4. Bundle average delivery delay as function as reputation nodes threshold for Spray and Wait routing protocol, considering SISD, DISD, SIDD, and SIMHD reputation mechanisms.

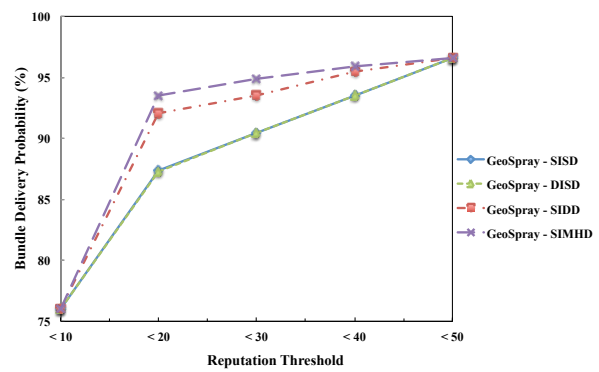


Fig. 5. Bundle delivery probability as function as reputation nodes threshold for GeoSpray routing protocol, considering SISD, DISD, SIDD, and SIMHD reputation mechanisms.

C. Performance Evaluation considering GeoSpray routing protocol

GeoSpray is a multiple-copy geographic routing protocol designed specially for VDTNs. This protocol exploits the mobility of vehicles and the location information provided by position devices (e.g., Global Positioning System), to support routing decision-making process. GeoSpray was designed to perform into sparse scenarios where communication opportunities are sporadic. GeoSpray also follows a hybrid approach inspired on GeOpps [16] and the binary version of Spray and Wait.

As may be seen in Figures 5 and 6, GeoSpray performs slightly better than Spray and Wait, presenting higher delivery ratios across all simulations, in this resource constrained network scenario. The effect of the proposed reputation approaches, as a strategy to increase the overall network performance by identifying and isolating selfish nodes, is even more pronounced in this routing protocol.

Figure 5 shows that when nodes follow the SIMHD scheme, the bundle delivery probability increases when compared with other schemes. When compared with the SISD scheme, it increases approximately 6%, 5%, and 3% (for reputation threshold equals to 20, 30, and 40, respectively). It also performs better than the DISD, by delivering approximately more 7%, 5%, and 3% (for reputation threshold equals to 20, 30, and 40, respectively). Finally, the SIDD delivers less 2%, 2%, and 1%, respectively, when compared with the SIMHD scheme.

In terms of bundle average delivery delay, the performance of GeoSpray present significant gains when compared to Spray and Wait. SISD and DISD schemes deliver bundles later and present a similar performance. However, SIMHD delivers bundles approximately 71, 37, and 9 second sooner (for reputation threshold equals to 20, 30, and 40, respectively) when compared to the SIDD scheme. Figure 6 also shows that the bundle average delay tends to decrease as the cooperation threshold value increase.

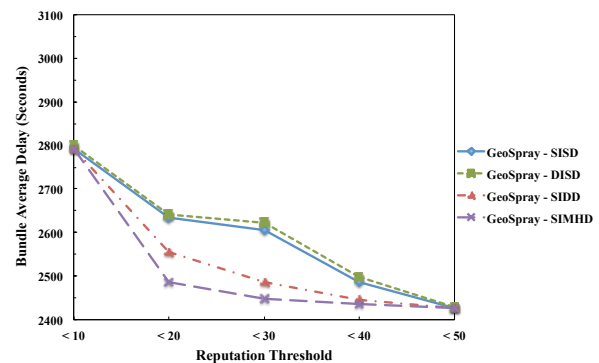


Fig. 6. Bundle average delivery delay as function as reputation nodes threshold for GeoSpray routing protocol, considering SISD, DISD, SIDD, and SIMHD reputation mechanisms.

D. Discussion

This subsection overviews and discusses the results obtained for all the conducted studies, considering different reputation mechanisms. As may be seen in the last two subsections, reputation functions that penalize selfish nodes in a more aggressive way contributes to improve the overall network performance by increasing the number of delivered bundle and decrease the bundle average delivery delay. This network improvement may also be confirmed, taking into account the number of dropped bundles.

The same functions (SIMHD and SIDD) contributes to a significantly reduction of the number of dropped bundles. When Spray and Wait is considered, the SIMHD discards less 101, 90, and 41 bundles (for cooperation threshold equals to 20, 30, and 40, respectively) when compared SIDD reputation scheme. When compared to other type of schemes, the SIMHD discards less 369, 269, and 149 bundles when compared to SISD reputation scheme, and less 401, 207, and 84 bundles when compared to DISD reputation scheme.

Following the same behavior observed in Spray and Wait, the SIMHD reputation function when enforced in GeoSpray routing protocol also contributes to decrease the number of

dropped bundles. When compared to the SIDD function it drops less 113, 107, and 51 (for cooperation threshold equals to 20, 30, and 40, respectively). The other two reputation functions (SISD and DISD) have a similar performance dropping more 481, 347, and 200 bundles when compared to the SIMHD function.

V. CONCLUSION AND FUTURE WORK

In the last years vehicular architectures have been the focus of investigation not only by the scientific community but also by the automotive industry. Vehicular Delay-Tolerant Networks have been proposed as a possible solution to overcome the most challenging issues of vehicular communications. However, VDTNs still face several challenges on data communications due to sparse and intermittent connectivity, or even the absence of an end-to-end path between the source and destination nodes.

This paper focuses on nodes cooperation and how selfish nodes may influence the overall network performance. To reduce the impact of such nodes a reputation system was proposed and enforced in VDTNs. This scheme implements four different ways to reward/punish nodes, and their performance was evaluated considering two different protocols (Spray and Wait and GeoSpray). It was shown that schemes that penalizes in a more aggressive way selfish behaviors contribute to increase the overall network performance (the number of delivered bundles increase and the number of dropped bundles decrease). The GeoSpray routing protocol performs significantly better than Spray and Wait.

This work may be used as a base to develop more complex reputation strategies that contributes to an increase of the overall network performance. Monitoring and management strategies may also be development to help nodes saving network resources. Both proposals may be suggested for further research works.

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A hybrid system to stimulate selfish nodes to cooperate in VDTNs

Appendix B

A hybrid system to stimulate selfish nodes to cooperate in Vehicular Delay-Tolerant Networks

This appendix is based on the following paper:

A hybrid system to stimulate selfish nodes to cooperate in Vehicular Delay-Tolerant Networks

João A. F. F. Dias, Joel J. P. C. Rodrigues, N. Kumar, and Constandinos X. Mavromoustakis

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A Hybrid System to Stimulate Selfish Nodes to Cooperate in Vehicular Delay-Tolerant Networks

João A. F. F. Dias¹, Joel J. P. C. Rodrigues^{1,2}, Neeraj Kumar³, Constandinos X. Mavromoustakis⁴

¹Instituto de Telecomunicações, University of Beira Interior, Portugal

²University ITMO, St. Petersburg, Russia

³Department of Computer Science and Engineering, Thapar University, Patiala (Punjab), India

⁴University of Nicosia, Nicosia, Cyprus

joao.dias@it.ubi.pt; joeljr@ieee.org; nehra04@yahoo.co.in; mavromoustakis.c@unic.ac.cy

Abstract— In the last decade vehicular communications have been the focus of research, not only by the related scientific community but also by the automotive industry. Several architectures were proposed in order to overcome some issues found in such networks. Vehicular Delay-Tolerant Networks (VDTNs) try to improve vehicular communications by deploying the Delay-Tolerant Networks (DTNs) store-carry-and-forward model and assuming the bundle layer placement under the network layer. Although all the improvements already achieved by VDTNs, there are still several challenges that must be overcome. One of these challenges is how to stimulate nodes to cooperate and minimize the impact of misbehavior nodes on the network performance. A node may be unwilling to cooperate due to a selfish behavior or to save its own resources from being compromised. To detect, isolate, and exclude this type of nodes a reputation system with different mechanisms (allowing to punish selfish nodes in different ways) was implemented in VDTNs. This paper adapts the already proposed reputation system to perform together with a hybrid system, which main goal is to incentive selfish nodes to share their resources with others, instead of immediately excluding them from the network. With the proposal of this hybrid system, two incentive mechanisms were also created. Across all the experiments, it was shown that by incentive selfish nodes to cooperate contributes to an increase of the overall network performance, when compared to an approach that excludes them immediately from the network.

Keywords— Vehicular Delay-Tolerant Networks; Cooperation; Reputation Mechanisms; Hybrid Approach; Selfish Nodes; Performance Evaluation

I. INTRODUCTION

Over the last years, Vehicular Delay-Tolerant Networks (VDTNs) [1, 2] have emerged to allow a diversity of mobile and fixed nodes to freely interact among them. Gathering several contributions from Vehicular Ad-hoc Networks (VANETs) [3], Delay-Tolerant Networks (DTNs) [4], and Optical Burst Switching Networks (OBS) [5], VDTNs follow a network architecture based on three major principles: *i*) an Internet Protocol (IP) over VDTN approach; *ii*) an end-to-end asynchronous and variable-length bundle oriented communication; and *iii*) a separation between control and data planes, performing out-of-band signaling.

The VDTN architecture considers three different types of nodes: mobile, terminal, and relay nodes. Mobile nodes (i.e., vehicles) are opportunistically exploited to collect and disseminate data. They move along roads and carry data that must be delivered to terminal nodes. Terminal nodes are fixed devices that are access points to the VDTN network, thus acting as traffic sources and/or traffic sinks. Stationary relay nodes are fixed devices with store-and-forward capabilities that are usually located at road intersections. They are used to improve the number of contacts opportunities in scenarios with low node density. Thus, they can contribute to increase the bundle delivery probability and to decrease the bundle average delivery delay [6]. Mobile nodes use them to deposit and pickup data.

VDTN architecture also considers a DTN store-carry-and-forward routing protocol. However, contrary to DTN approach, this routing protocol introduces the bundles layer under the network layer. This approach allows VDTNs to introduce two logical planes (control and data plane), supporting out-of-band signaling. In VDTNs, the data plane assembles, transmits, and processes data bundles, while the control plane is responsible for the transmission and processing of signaling messages. This approach ensures the optimization of the available data plane resources (e.g., storage and bandwidth), but also allows power saving, which is very important for energy-constrained network nodes, such as stationary relay nodes [2, 7].

Recent studies considering this architecture contributed to overcome some issues found in vehicular communications. However, there are still a number of technical issues that must be overcome. One of these issues is how nodes must cooperate in order to improve the overall network performance and avoid selfish nodes. Conducted studies on this field [8] shown that applying cooperation in VDTNs is not an easy task. It is important to stimulate nodes to cooperate in order to create an optimal cooperative system that increase the overall network performance without comprising or deteriorating nodes data. To create an optimal cooperative system it is important to considered two types of nodes: cooperative and selfish. Cooperative nodes share their own resources to store-carry-and-forward bundles from other nodes. By the other hand, selfish nodes are unwilling to cooperate and in most cases they receive bundles forwarded by other nodes to drop them

immediately. The performance of selfish nodes may affect the performance of cooperative nodes.

To minimize the impact of selfish nodes on the overall network performance, this paper proposes a hybrid system with a different approach to deal with this type of misbehavior nodes. Contrary to the already proposed reputation system [9], that immediately excludes nodes when they are marked as selfish nodes, this system takes advantages of nodes reputation score to classify them. This score is used to calculate which nodes present a selfish behavior in order to encourage them to cooperate (for pre-defined period of time). Nodes are excluded from the network if they maintain their selfish behavior, despite the system incentive. Thus, the main contributions of this paper are the following:

- A review of the state of the art considering the most relevant contributions on reputation and incentive systems for vehicular networks;
- Proposal of a hybrid system combining the best features of a reputation mechanism with a monitoring module that takes advantages of incentive mechanisms;
- Proposal of two mechanisms to incentive selfish or misbehavior nodes to cooperate;
- Exhaustive studies to evaluate the performance of VDTNs considering the proposed system, using the most relevant routing protocol;

The remainder of this paper is organized as follows. Section II focuses on the cooperation problem and briefly reviews the literature on cooperation in vehicular networks. Section III describes the main features of the hybrid approach and how it can be enforced in VDTNs. Section IV presents the experimental settings and the performance metrics considered across all the experiments, whereas Section V discusses the performance assessment of the proposed system enforced on VDTNs. Finally, Section VI concludes the paper providing a final summary of the study and points several research guidelines for future works.

II. RELATED WORK

Cooperation among network nodes is a very interesting topic of investigation in vehicular networks, because it not only contributes to improve the way nodes carry messages from source to destination, but also allows the proposal of different applications and services. However, cooperation between nodes may become a problem if they diverge from the protocol due to a selfish behavior or to save their own resources. In both situations, the performance of such nodes contributes to a significant decrease on the network performance.

In order to improve the overall network performance, reputation systems should be developed to allow nodes to detect, identify, and avoid selfish nodes. In the literature, several reputation systems were proposed. For example, in [10] a reputation system for ad-hoc networks that identifies and isolates selfish nodes is presented. In this system, different reputation heuristics are considered to allow nodes to autonomously evaluate the reputation of its neighbors based on the completion of the requested service. Conducted studies with this system shown that choosing the way nodes are

punished by their selfish behavior, leads to a network performance improvement.

A reputation system called VARS [11] that uses a reputation score to identify selfish nodes were proposed and implemented in VANETs. To calculate a node reputation score, network nodes use an opinion generation and the confidence of this decision. Each time a node receives a message from other node, it generates its own opinion based on the trustworthiness of the message. In order to calculate the opinion, nodes may consider partial opinions that came attached to the message or other nodes opinion. When a node forwards a message, it attaches to this message its own opinion.

In [12], another reputation system for VANETs is proposed. This system considers a long-term system that provides reliable reputation scores by taking advantages of nodes daily trajectories. To build long-term reputations scores, the roadside infrastructure rely its opinion on repeated daily observations of the same set of passing-by vehicles. To ensure nodes trustworthiness, this system requires that each node have a secret key and a verifiable certificate.

Cooperative ARQ scheme (C-ARQ) [13] was proposed to stimulate nodes to cooperate in DTNs. The main goal of C-ARQ is to reduce the number of packet losses in transmissions between fixed access points (placed along roads) and passing-by vehicles. This scheme takes advantages of vehicles to enable communications in places out of the range of access points. A variant of this scheme (DC-ARQ) were also proposed in [14]. This scheme differs from the above by performing cooperation between network nodes until they are out of range of access points. In C-ARQ cooperation occurs based on a packet-by-packet approach.

Several studies were already conducted in order to analyze the impact of cooperation mechanisms in VDTNs. In [15] a preliminary study about the impact of cooperation in VDTNs were conducted. Based on this preliminary study, four different cooperative strategies [8] to force nodes to share their own resources were proposed and their impact on the performance of VDTNs were evaluated. A reputation scheme considering four different heuristics to identify, isolate and avoid selfish nodes were proposed in [9]. This system uses a reputation score calculated based on nodes performance. Each time a node successfully delivers a bundle its reputation score is increased according to the chosen reputation heuristic. By the other hand, each time a node drops a bundle without send it once it is punished. Performance studies shown that using a reputation system in VDTNs contributes to a significant gain on the network performance.

This section overviewed the most important advances in cooperation in vehicular communications. They may be considered as a starting point to propose new mechanisms or systems to deal with misbehavior nodes in VDTNs.

III. HYBRID SYSTEM MODEL

The presence of selfish nodes in VDTNs severely affects their performance. In order to optimize the overall network performance, when a selfish node is detected, several actions may be performed. Selfish nodes may be isolated and excluded from the network, or may be encouraged to change their

behavior in order to contribute to the maintenance of an optimal network performance.

This section elaborates on the description of the proposed hybrid system, aiming to deal with the presence of selfish nodes in VDTNs. The architecture of the hybrid system consists of two components: Reputation module and Monitoring module. The first sub-section overviews the reputation system workflow, while the second sub-section describes the monitoring system, which main goal is to incentive selfish nodes to cooperate with other network nodes.

A. Reputation Module

The reputation module was proposed in [9], and was adapted to operate together with the monitoring module. This module builds in each node a reputation table containing important information (e.g., node ID or reputation score), about all the encountered nodes. Taking advantages of the VDTN out-of-band signaling process, each time a contact opportunity is available, the reputation score of the encountered node is updated. Nodes reputation score is used to compare it with a network reputation threshold (α) equal to all the network nodes. This allows the proposed system to detect and classify nodes into two categories: cooperative and selfish nodes. If nodes reputation score is higher than α then they are marked as cooperative nodes, otherwise, they are marked as a selfish node and added to the monitoring table.

B. Monitoring Module

The monitoring module operation is based on an incentive approach, which tries to stimulate nodes to cooperate by offering them rewards in exchange of their cooperation. Considering this approach, when the reputation module marks a node as a selfish node, the monitoring module begins to monitor it. Being monitored by this system means that during a period of time (C_i) a selfish node is encouraged (e.g., bundles generated from a monitored node will have priority relative to bundles generated from other nodes) to share its own resources with other nodes to continue being part of the network. After this period of time, if the node continues to maintain its selfish behavior it is permanently excluded from the network. However, if the node changes its behavior and starts sharing its own resources with others during the pre-defined C_i time, the system reward it by updating its reputation score according to their performance on each contact opportunity. This process is repeated until the node reputation score reach the same value of the network reputation score or until the C_i time expires. From this moment, nodes are marked as partial cooperative nodes and continue to consume network resources. If a partial cooperative node is marked as a selfish node by the reputation module it is automatically excluded from the network. Figure 1 illustrates the hybrid system workflow.

C. Incentive Mechanisms for Selfish nodes

The reputation heuristics previously proposed [9] consider the number of delivery and dropped bundles as metrics to update nodes reputation score. This heuristics cannot be applied to stimulate selfish nodes because if a node is marked as a selfish node it means that this node dropped much more bundles than those who delivered. For this reason, two new heuristics are proposed: VBT (*Volume of Bytes Transferred*)

and TSC (*Time Spent to Cooperate*). The main idea behind these two heuristics is to reward selfish nodes by their effort to forward bundles. In the VBT heuristic, each time a node successfully forward a bundle, its reputation score increases $2k + h*k*v$ units, where k is a constant value, h is the number of bundle hops between the source and the current node, and v is the percentage of bytes transferred by the forwarding node. Equation (1) shows how v is calculated for each node, where BT_i is the number of bytes transferred by node i .

$$v = \frac{BT}{\sum_{i=1}^N BT_i} * 100 \tag{1}$$

The TSC heuristic considers the time that a node spent cooperating with other networks nodes to reward them. Each time a node forward a bundle, its reputation score increases $2k + h*k*t$ times, where t is the percentage of time spent by a node cooperating with other nodes. Equation (2) shows how t is calculated for each node, where TC_i is the time spent by node i cooperating with other nodes.

$$t = \frac{TC}{\sum_{i=1}^N TC_i} * 100 \tag{2}$$

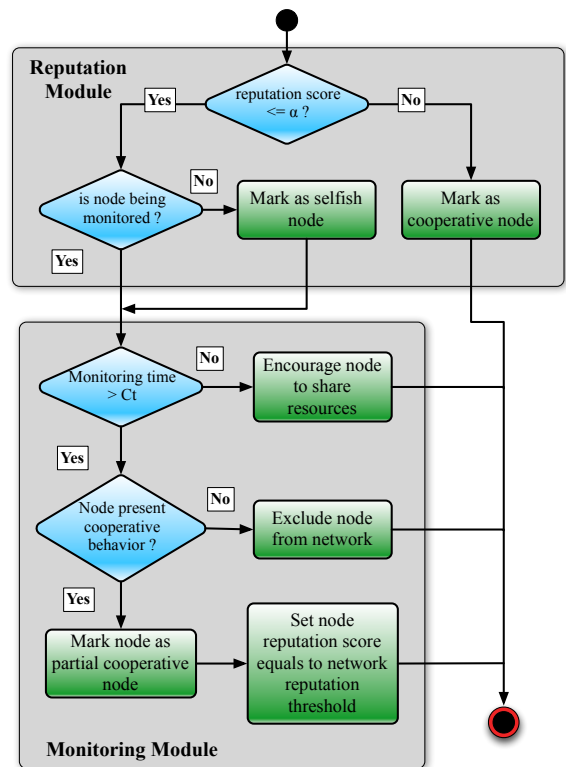


Fig. 1. Illustration of the hybrid system workflow deployed in VDTNs.

IV. NETWORK SETTINGS

Performance studies are conducted through simulation considering the VDTNsim tool [16], which is an extension of

the ONE simulator [17, 18] that allows to introduce the store-carry-and-forward overlay network below the network layer. Across all the simulation experiments, a map-based representation of a part of the city of Helsinki, Finland (Figure 2) is considered. It is assumed a cooperative opportunistic environment without knowledge of the traffic matrix and contact opportunities for a period of 12 hours (e.g., 9:00 to 21:00).

This scenario considers 10 terminal nodes acting as traffic sinks, each one with a 50 MB (MegaBytes) buffer. During the simulated 12 hours period of time, 100 vehicles (e.g., mobile nodes) move between terminal nodes with a buffer capacity of 25 MB. When a mobile node reaches a terminal node, it randomly waits between 15 and 30 minutes. Then, it randomly selects its next destination node. All mobile nodes move along roads using the shortest path available, with an average speed of 50 km/h. These mobile nodes may also interact with 5 relay nodes, each one with a 100 MB buffer, placed at the selected crossroads presented in Figure 2. The percentage of mobile nodes with selfish behavior changes between 10, 20, 30, 40, and 50 percent, across the simulations. Increasing the number of selfish nodes will allow studying the impact of the proposed system with the new incentive metrics in order to encourage misbehavior nodes to share their own resources for the benefit of the network. All network nodes connect to each other using IEEE 802.11b with a data rate of 6 Mbps, and a transmission range of 350 meters using omni-directional antennas.

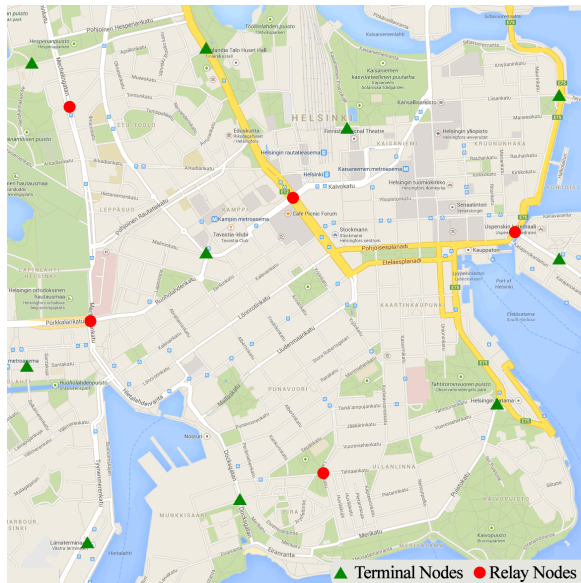


Fig. 2. Illustration of the Helsinki downtown (Finland) map (area of 4500x3400 meters), with the location of terminal nodes and the stationary relay nodes.

Data bundles are generated at random mobile nodes (i.e., traffic sources) and are destined to random terminal nodes using an inter-bundle creation uniformly distributed in the range of [25, 35] seconds. Each mobile node generates bundles with sizes uniformly distributed in the ranges of [25 KB, 100 KB], [250 KB, 500 KB], and [750 KB, 1 MB] (bytes)

respectively. All bundles generated during the simulation experiments have a time to live (TTL) of 180 minutes. For all the simulation experiments, the GeoSpray routing protocol [19] was considered.

Performance metrics considered in this study are the number of delivered bundles, the bundle average delivery delay, and the percentage of dropped bundles. The bundle average delivery delay is defined as the average time between bundles creation and delivery. It is calculated according to Equation (3), where D_D is the bundle average delivery delay, T_{d_i} is the time when the bundle i was delivered, T_{c_i} is the time when the bundle i was created, and D_B is the total number of unique delivered bundles. The percentage of dropped bundles (P_{DB}) is defined as the ratio between the total number of dropped bundles and the total number of bundles that was created at the source node(s). It is calculated according to Equation (4), where P_{DB} is the percentage of dropped bundles, N_{DB} is the number of dropped bundles, and N_{CB} is the total number of created bundles.

$$D_D = \frac{\sum_{i=1}^{D_B} (T_{d_i} - T_{c_i})}{D_B} \quad (3)$$

$$P_{DB} = \frac{N_{DB}}{N_{CB}} * 100 \quad (4)$$

V. PERFORMANCE ASSESSMENT

This section focuses on the performance evaluation of the proposed hybrid system and how it affects the performance of VDTNs. To analyze its impact, after marking nodes as selfish, the hybrid system asks this kind of nodes to share their own resources for a period of time (C_i) equal to 60 minutes. The network reputation threshold is equal to 10. This means that a node is marked as a selfish node by the reputation module, when its reputation score is lower than 10. The performance studies start with the comparison of the two incentives mechanisms in respect to the number of delivered bundles, when the hybrid system is considered.

As may be seen in Figure 3, both schemes contribute to the increase of the number of delivered bundles when selfish nodes are detected in the network. The TSC approach delivers more 40, 98, 83, 156, and 247 bundles (for a percentage of selfish nodes equals to 10, 20, 30, 40, and 50, respectively) when compared with an approach where selfish nodes are immediately excluded from the network. By the other hand, the VBT approach delivers more 51, 76, 87, 109, and 177 bundles when compared with the approach where selfish nodes are immediately excluded. This allow us to conclude that encourage selfish nodes to cooperate is a possible solution to decrease the negative impact of these misbehavior nodes in the overall network performance.

Figure 4 shows the obtained results for the bundle average delivery delay. As expected, by encourage selfish nodes to share their own resources with others to improve the overall network performance, leads to an increase of the number of hops and consequently to an increase of the time that bundles

need to travel from the source to the destination node. However, the increase of time is not significant when compared to an approach where selfish nodes are immediately excluded from the network. For example, encouraging nodes with the TSC approach, make bundles being delivered approximately 3, 4, 5, 6, and 8 minutes later (for a percentage of selfish nodes equals to 10, 20, 30, 40, and 50, respectively). With the VBT approach, bundles are delivered 2, 3, 4, 3, and 5 minutes later, when compared to the excluding approach.

Figure 5 confirms the obtained results showing that encouraging selfish nodes to cooperate is a good way to decrease their malicious impact on the network performance. As may be seen, both mechanisms contribute to the network resources optimization by decreasing the amount of dropped bundles. The TSC approach leads to drop approximately less 1%, 2%, 2%, 3%, and 5% of bundles (for a percentage of selfish nodes equals to 10, 20, 30, 40, and 50, respectively), when compared to an approach that immediately excludes selfish nodes. The VBT approach follows a similar behavior, dropping approximately less 1%, 2%, 3%, 2%, and 5% bundles.

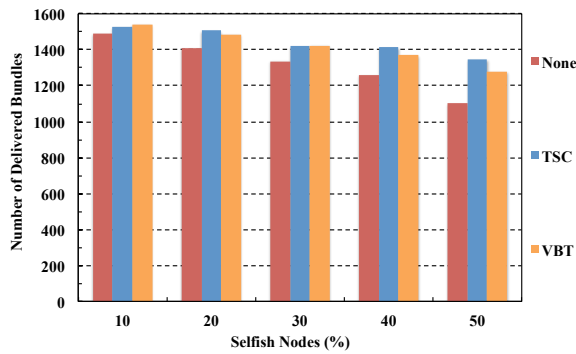


Fig. 3. Number of unique delivered bundles as function of the percentage of selfish nodes, considering the GeoSpray routing protocol and a network reputation threshold equals to 10.

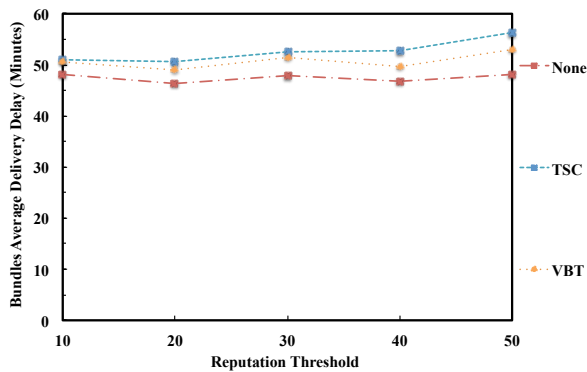


Fig. 4. Bundle Average Delivery Delay as function of the percentage of selfish nodes, considering the GeoSpray routing protocol and a network reputation threshold equals to 10.

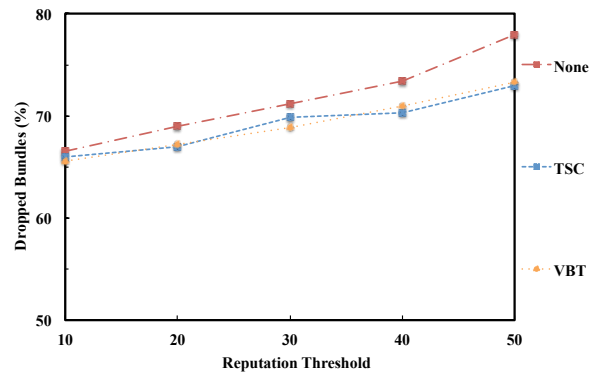


Fig. 5. Percentage of dropped bundles as function of the percentage of selfish nodes, considering the GeoSpray routing protocol and a network reputation threshold equals to 10.

VI. CONCLUSION AND FUTURE WORK

Vehicular delay-tolerant networks have been emerging as a possible solution to overcome several issues presented by vehicular communications. However, VDTNs still have to overcome some of these issues in order to continue improving the overall network performance.

This paper focused on cooperation between network nodes and how selfish nodes affect the overall network performance. In order to reduce the impact of selfish nodes, a hybrid mechanism, combining the best of both reputation and incentive approaches, was proposed. With this system it is intended to stimulate selfish nodes to cooperate. Two new incentive mechanisms were also implemented and their performance was evaluated. Obtained results (considering the number of delivered bundles, bundles average delivery delay, and dropped bundles) confirm that encourage selfish nodes to share their own resources to help others deliver bundles is a possible approach to reduce their malicious impact on the network performance. Tables I, II, and III summarize the obtained results conducted through simulation studies and presented in this paper.

TABLE I. NUMBER OF DELIVERED BUNDLES

Approach	% Selfish Nodes				
	10	20	30	40	50
None	1489	1409	1337	1260	1102
TSC	1529	1507	1424	1369	1279
VBT	1540	1507	1420	1416	1349

TABLE II. BUNDLE AVERAGE DELIVERY DELAY (MINUTES)

Approach	% Selfish Nodes				
	10	20	30	40	50
None	48	46	48	47	48
TSC	51	50	53	53	56
VBT	50	49	52	50	53

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TABLE III. PERCENTAGE OF DROPPED BUNDLES

Approach	% Selfish Nodes				
	10	20	30	40	50
None	67	69	71	73	78
TSC	66	67	69	70	73
VBT	66	67	68	71	73

For future research work, in order to seek for network performance improvements by increasing the bundle delivery probability and helping nodes saving resources, monitoring and management strategies may be developed.

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Appendix C

MoM - A Real Time Monitoring and Management Tool to Improve the Performance of Vehicular Delay-Tolerant Networks

This appendix is based on the following paper:

MoM - A Real Time Monitoring and Management Tool to Improve the Performance of Vehicular Delay-Tolerant Networks

João A. F. F. Dias, Joel J. P. C. Rodrigues, Juan F. de Paz, and Juan M. Corchado

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MoM - A Real Time Monitoring and Management Tool to Improve the Performance of Vehicular Delay Tolerant Networks

João A. F. F. Dias¹, Joel J. P. C. Rodrigues^{1,2}, Juan F. de Paz², Juan M. Corchado²

¹Instituto de Telecomunicações, Universidade da Beira Interior, Covilhã, Portugal

²University of Salamanca, Spain

joao.dias@it.ubi.pt; joeljr@ieee.org; fcofds@usal.es; corchado@usal.es

Abstract— Vehicular Delay Tolerant Networks (VDTNs) appears as an innovative approach to deal with several issues faced by vehicular communications. By exploiting vehicles and deploying a DTN store-carry-and-forward paradigm with an Internet protocol over VDTN it is possible to enable asynchronous communications in the absence of end-to-end links. VDTNs also combine a bundle-oriented communication with an out-of-band signaling approach. To ensure that network nodes follow the protocol contributing to the welfare of the network, network monitoring and management functions play a key role. This paper proposes and describes a monitoring and management tool for VDTNs, called MoM, which collects real-time information from the network in order to improve the overall network performance. Conducted studies shown that MoM contributes to increase the bundle delivery probability and decreases the amount of wasted resources.

Keywords — Vehicular delay tolerant networks (VDTN); Network monitoring; Network management; Performance evaluation

I. INTRODUCTION

Lately, the search for Intelligent Transportation Systems (ITS) [1] that enable low-cost communications attracted significant attention from both scientific community and industry. From this demand, several vehicular networking approaches have been proposed enabling communications in a wide variety of scenarios. Such approaches also allow proposing novel applications and services. Networks for safety information dissemination, monitoring networks for data collection, and networks to share multimedia content are some examples. Vehicular networks may also be considered to provide connectivity to remote or rural regions where there is a lack of network infrastructure, which does not allow having an end-to-end connectivity. Although the advances already achieved by this kind of networks, there are still work to be done in order to deal with several challenges. For example, the high mobility of vehicles leads to frequent network topology changes and short contact durations, which can lead to several problems in achieving successfully data communications [2].

Trying to overcome some of the above-mentioned issues, some vehicular architectures have been proposed. Vehicular Ad Hoc Networks (VANETs) [3] exploit vehicles to enable

data communications assuming that routing protocols establish end-to-end connectivity. This conjecture turns VANETs suitable to network partition, disconnection, and long delays. The store-carry-and-forward paradigm proposed by Delay Tolerant Networks (DTNs) [4] helps vehicular communications to solve some of the open issues found in VANETs. More recently and gathering some contributions from the previous architectures, such as the DTN store-carry-and-forward paradigm, Vehicular Delay Tolerant Networks (VDTNs) [5] were proposed with deployment of out-of-band signaling with two independent planes: control and data. VDTNs are also characterized to operate over the link layer allowing to aggregate large IP (Internet Protocol) datagrams sharing the same characteristics into bundles [6]. Bundles represent the VDTN protocol data unit. VDTNs also consider three different types of nodes: mobile, terminal, and relay. Mobile nodes (e.g., vehicles) travel between terminal nodes, which act as access points to the VDTN network and may perform as traffic sources and traffic sinks. Relay nodes are fixed devices with large storage capacity, usually placed at crossroads, aiming to improve the number of contact opportunities.

Although some improvements were already achieved by vehicular communications, there are still some technical challenges that must be overcome, such as the highly dynamic network topology, network disruption, node interactions, and limited network resources. Furthermore, limited network resources are one of the major problems faced by vehicular networks. Nodes with limited resources tend to diverge from the protocol in order to keep their data integrity. For example, they may deny contacts with other nodes to keep their data integrity, or in the other hand, if they accept a contact opportunity with other node, they may have to drop some messages (leading to messages loss) to have enough space to receive new ones. This situation has huge consequences not only in the overall network performance but also in the performance of other nodes.

To decrease the impact of such behavior in the network it is very important to afford vehicular networks with sophisticated tools that can rapidly and accurately detect network anomalies and constraints contributing to improve the overall network performance. This paper proposes a tool for VDTNs, called MoM, that operates in real time allowing to not only

monitoring but also performing management actions. Thus, the paper reviews the related literature considering the most relevant contributions on monitoring and management approaches for delay-tolerant and vehicular communications, proposes an accurate tool capable to perform both monitoring and management functions in VDTNs, and executes studies to evaluate the performance of VDTNs considering the proposed tool using the most relevant routing protocols.

The remainder of this paper is organized as follows. Section II overviews several monitoring and management solutions proposed for delay tolerant and vehicular networks. Section III describes the main principles and characteristics of MoM, while Section IV focuses on its performance evaluation and demonstration. Finally, Section V concludes the paper pointing some future work.

II. RELATED WORK

This section overviews the most relevant contributions related to network monitoring and management approaches proposed for delay-tolerant and vehicular communications, which may contribute to the development of MoM.

Wang *et. al* [7] proposed a compressive sensing based approach, called CSM, for vehicular networks monitoring. It aims to achieve high estimation accuracy using vehicles measurements. To collect vehicles information, CSM sets a few number of vehicles as seeds. This kind of vehicle is responsible to collect data from regular vehicles and deliver it to network access points (APs). APs consider k-NN estimate and Gaussian process regression to process vehicles measurements.

In the study presented in [8], the authors proposed a framework that is capable to optimize the process of traffic monitoring. This optimization is achieved by two delay-tolerant routing protocols that collect vehicle information about traffic and global traffic statistics to accomplish routing forwarding strategy decisions that helps to minimize communication costs.

A monitoring and control system for DTNs is proposed in [9]. This system works in a distributed way allowing collecting the operational status of DTN nodes in order to detect operation failures and helps to seek solutions to solve these operational failures. Moreover, it also affords DTNs with a tool for diagnose and treatment failures where network operators may compose several failure treatment methods according to the collected reports. A set of monitoring mechanisms are presented in [10] to enable monitoring capabilities in the bundle and lower layers of the DTN architecture. These mechanisms focus on several important features, such as nodes available storage capacity, since the lack of storage capacity may lead to bundles loss. To gather network statistics the authors implemented ping bundles, which forces nodes to generate reports to be delivered to the monitor processor.

Nobre *et. al* [11] proposed a self-handling service to perform management functions in DTNs considering peer-to-peer technologies. The service exploits the DTN concept to support and grouping management messages, and it can be used by system administrators for monitoring and heal managed network elements.

In [12], the authors proposed several policies to deal with buffer management in DTNs using global knowledge about the network. With a distributed algorithm that learns from the collected statistical data, these policies managed to increase the average delivery rate and drop the average delivery delay. Another buffer management policy is proposed in [13]. This policy has the capability to prioritize messages in nodes buffer allowing maximizing the successful delivery rate in the entire network. This is accomplished considering a generic replication-based routing model for message multicasting. A similar approach is followed by the work proposed in [14].

Regarding VDTNs, several proposals for monitoring and management purposes were already proposed. They take into consideration MMAN [15], which uses mobile nodes to perform monitoring functions and a set of monitoring stations to create an accurate update state of the network. An example of this is an application-layer approach [16] proposed to collect load-related information from VDTN nodes considering the Simple Network Management Protocol (SNMP). In [17], a management system to perform management functions using SNMP is proposed. Contrary to both approaches that uses SNMP to only perform monitoring or management functions, the proposal of MoM takes advantages of a backbone system and the VDTN out-of-band signaling to perform both monitoring and management functions.

III. MoM SYSTEM

This section describes the main characteristics and functionalities of MoM tool proposed for VDTNs. Its main goal is to afford VDTNs with an accurate tool capable to not only perform monitoring functions but also to take measures, in real time, when some network constraint is detected.

A. Main Concepts

As above-presented, the VDTN architecture deploys an out-of-band signaling with control and data plane separation. At the control plane nodes exchange signaling messages containing crucial information about their state (e.g., buffer capacity, power, location, and speed) that can be used not only to reserve resources to the data plane but also to evaluate their performance in the network.

The MoM tool takes advantages of this architectural approach to collect statistical information about the performance of each network node and to spread across the network measures to held constraint nodes or to take actions against nodes responsible for decreasing the network performance. To perform both monitoring and management functions, MoM requests nodes to collect reports about three kinds of statistics: node state, bundles traffic, and link statistics. Node state information is related to nodes available buffer space, speed, and location. Bundle traffic information is related to how many bundles each node receives, transmits, delivers, and drops, while link statistics allows MoM to know the amount of data transmitted and the amount of time a node spend to communicate with others.

An example of MoM operation can be described as follows. Each mobile node during its tour along the network keeps record of the number of delivered, sent, received, aborted, and dropped bundles. It also collects the volume of bytes

exchanged and the amount of time spent in contact with other nodes. When a contact opportunity with a terminal node is available, it uses the control plane to send its statistical report. Then, terminal nodes send the received data to MoM to be processed. MoM processes the received information considering three different modules: monitor module, management module, and interface module. In case of network constraint detection, an advertisement is generated and spread across the VDTN network. Figure 1 illustrates the interactions between network nodes and MoM.

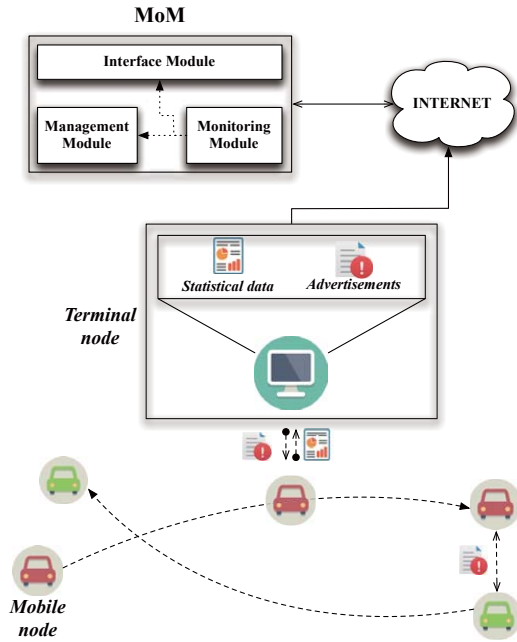


Fig. 1. Illustration of the interactions and exchanged data between MoM and VDTN network nodes.

B. Monitoring Module

The monitoring module is responsible to process mobile nodes reports and to keep updated a network state table containing all the relevant information about each network node. After processing the received data, it updates the state table and sends the updated information to the interface module in order to be presented to network administrators. At the same time, the monitor module evaluates each network node behavior assigning a performance coefficient (P). This coefficient is calculated according to Equation 1, where S is the number of sent bundles, D the number of bundles delivered to the final destination, C the amount of time spent communicating with other nodes, and V the total volume of bytes exchanged with others. All the considered values are normalized to an interval between $[0,1]$ considering (2). After calculating all the network nodes performance coefficient, it

calculates the performance coefficient for the entire network (N_p) that is determined by Equation 3. Each time the monitoring module detects that a node has a P below N_p it notifies the management module.

$$P_n = \alpha \cdot S_n + \beta \cdot D_n + \gamma \cdot V_n + \delta \cdot C_n \quad (1)$$

where α , β , γ , and δ = constant values

$$X_{normalized} = \frac{x - \min(x)}{\max(x) - \min(x)} \quad (2)$$

$$N_p = \frac{\sum_{i=1}^N P_i}{N} \quad (3)$$

Another constraint the monitoring module is always searching is for nodes closer to reach their full buffer capacity. This situation can contribute to the network performance deterioration since nodes with low buffer space may be forced to drop bundles to continuing receiving bundles from other nodes. This can lead to drop bundles that do not have any copy in the network comprising their changes to reach the final destination. To overcome this situation, each time a node with low buffer capacity is detected, the management module is informed.

C. Management Module

This module is responsible to generate network advertisements when it is notified by the monitor module. These advertisements are generated aiming to inform nodes about a behavior they must adopt or an action they must have against others. For example, the management module may generate an advertisement to alert nodes that a node is closer to reach its full buffer capacity. Receiving this kind of advertisement may lead nodes to avoid contacts with constraint nodes in order to not only save networks resources but also to prevent bundles to be dropped without reaching their final destination. Another example of advertisement that is generated by this module is an advertisement requesting a specific node to spend more time sending bundles from others or to use a higher percentage of its buffer to store bundles from others. This approach aims to increase the performance of nodes where P is below N_p . All advertisements generated by the management module are sent to terminal nodes in order to being spread across the network.

D. User Interface Module

This module is used to display to network administrators the state of the monitored VDTN. The information sent by the monitoring module is processed into two main categories: network performance and nodes state. For the network performance, the processed information is used to show real-time network performance graphs about bundles (e.g., created, delivered, delivered delay, sent, received, aborted, and dropped), contact time, and exchanged bytes. The network tab of MoM interface module is shown in Figure 2. The node state tab displays several characteristics about each network node, such as buffer total capacity, free buffer space, speed, and location. It is also possible to know detailed information about which bundles nodes were carrying last time they enter into contact with a terminal node. Figure 3 shows the nodes tab of the MoM interface module.

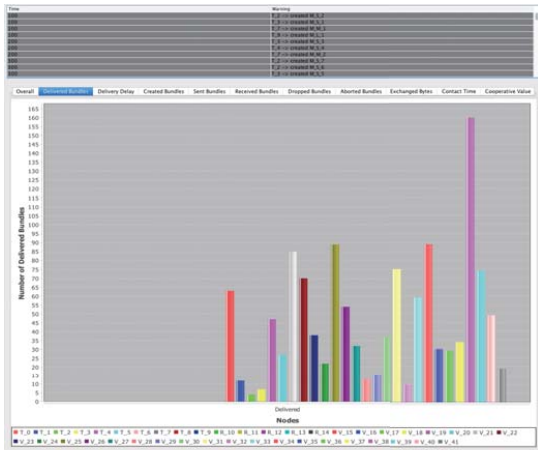


Fig. 2. Network tab of the MoM interface module showing a real-time graph about the number of delivered bundles by each mobile node.

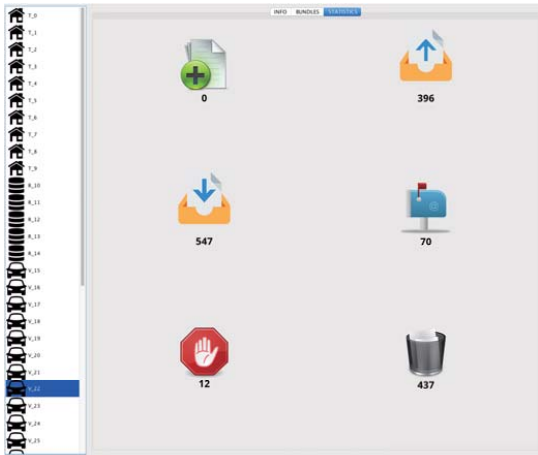


Fig. 3. Nodes tab of the MoM user interface module showing the number of created, sent, received, delivered, aborted, and dropped bundles for a specific node.

IV. MOM SYSTEM EVALUATION AND DEMONSTRATION

This section presents a case study to evaluate the performance of the MoM system and show the benefits it introduced in the VDTN architecture. The performance evaluation of MoM system was conducted through the VDTNSim [18] simulation tool.

A. Simulation Scenario

The simulation scenario considers a representation of a small part of the city of Helsinki, Finland (Fig. 4). During a simulation time of 24h, VDTN nodes establish communications among them considering a transmission range

of 350 meters enabled by IEEE 802.11b (at 6 Mbps) omnidirectional antennas. Ten terminal nodes with 100 MB of buffer capacity generate bundles with sizes uniformly distributed in the range of [50 KB, 750 KB] assuming a creation interval in a range of [30, 120] seconds. Five relay nodes with 200 MB of buffer capacity are placed according to the map positions illustrated in Figure 4. To create different evaluation scenarios to better evaluate the impact of MoM on VDTNs, the number of mobile nodes with 50 MB of buffer capacity changed between 25, 50, 75, and 100. In all the scenarios, the configuration of MoM parameters is set according to Table I. Performance metrics considered in all the experiments are the number of delivered bundles, the number of dropped bundles, and the protocol overhead ratio.

TABLE I. MOM PARAMETERS

Node Type	α	β	γ	δ
Terminal and Relay	0.7	0.0	0.15	0.15
Mobile	0.4	0.3		

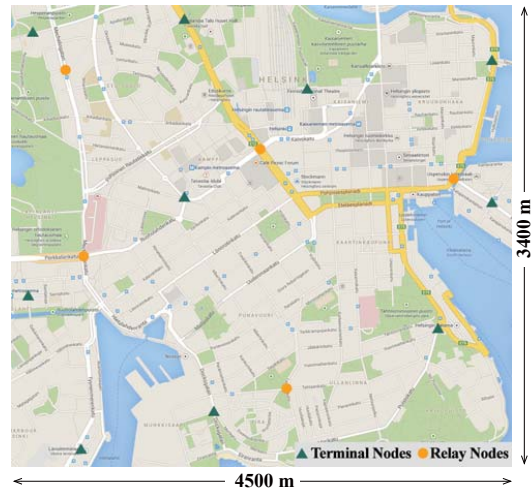


Fig. 4. Illustration of the map used to evaluate the performance of MoM, with the position of terminal and the stationary relay nodes.

B. Performance Analysis

The results obtained in the conducted experiments shown the importance of afford the VDTN architecture with a tool capable to handle some kinds of network constraints or diverging behaviors from network nodes. Figure 5 shows that followed approach by MoM system improves the overall network performance since more bundles are delivered to their final destination. This is achieved by constantly monitoring the network in searching nodes that are performing lower than the rest and requesting them to improve their contributions to achieve a better overall network performance. For instance, with the MoM tool activated the VDTN network achieves to

delivered more 56, 265, 157, and 236 bundles (for a number of mobile nodes equals to 25, 50, 75, and 100, respectively) when compared to a scenario without MoM.

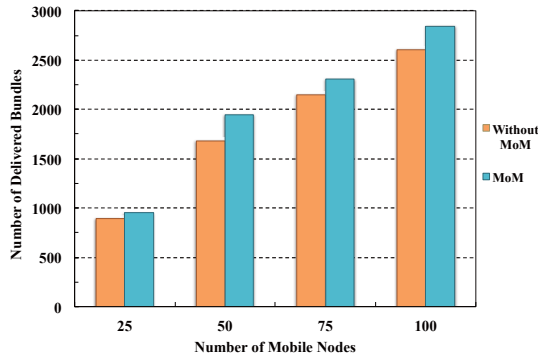


Fig. 5. Number of delivered bundles as function of the number of mobile nodes.

MoM contributions are not limited to the increase of the number of delivered bundles. It also contributes to reduce the amount of wasted resources. By detecting nodes closer to achieve their buffer capacity and spreading advertisements to the network, it allows other nodes to avoid contacts with constraint nodes. This approach allows nodes to avoid dropping unnecessary bundles to receive bundles from others. This may also contributes to increase the number of delivered bundles since it can be prevented that bundles are dropped at their final hop or without having any copy of them replicated across the network. Figure 6 confirms the above-presented conclusions. With MoM activated, VDTN network drops less 515, 781, 693, and 648 bundles. Consequently, this approach also contributes to decrease the protocol overhead ratio (Figure 7), which represents the number of bundle copies needed to deliver it to its final destination. These results demonstrated that MoM is also efficient not only in terms of storage but also in terms of bandwidth resources utilization.

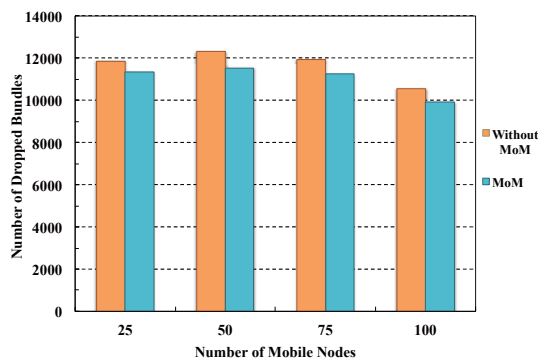


Fig. 6. Number of dropped bundles as function of the number of mobile nodes.

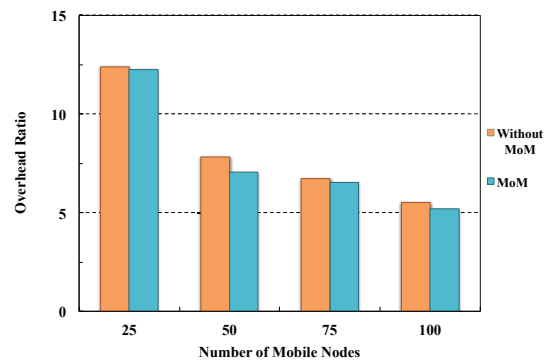


Fig. 7. Protocol overhead ratio as function of the number of mobile nodes.

V. CONCLUSION AND FUTURE WORK

This paper presented and evaluated the network performance of a real-time monitoring and management tool for VDTNs, called MoM. This robust and accurate tool constantly monitors the network searching for nodes with resource limitations or with a behavior that may compromise the overall network performance. When it finds an occurrence it generates advertisements with some guidelines that nodes should follow. These advertisements are spread across the network taking advantages of the VDTN out-of-band signaling at the control plane phase.

Performance studies showed that MoM tool benefits to achieve a better network performance when compared to an approach where nothing is considered. With MoM the number of delivered bundles increases and the amount of resources wasted decreases. Future work may focus on the deployment and performance evaluation of MoM in a laboratory VDTN testbed [19].

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