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Performance Assessment of Vehicular Delay-Tolerant Networks

Vasco Nuno da Gama de Jesus Soares

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Orientador: Prof. Doutor Joel José Puga Coelho Rodrigues

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Dedication

To my wife, Cláudia Soares, and my son, Francisco Soares, for their love, support and encouragement.

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Abstract

Vehicular networks have attracted considerable attention in the last few years, both in academia and industry. One of the main reasons for their growing popularity can be attributed to the various applications that they make possible. Road safety, traffic monitoring, driving assistance, entertainment, and delivering connectivity to rural/remote communities or catastrophe-hit areas are just a few examples of the many applications envisioned for these networks. Nevertheless, the special characteristics of vehicular networks such as high mobility, highly dynamic network topology, short contact durations, disruption, intermittent connectivity, significant loss rates, variable node density, and network partitioning introduce unique challenges, which greatly impact the deployment of these networks.

Such challenges make data dissemination and routing interesting research topics within the vehicular networking area, which are addressed by this research. The work presented in this thesis is motivated by the need to find new solutions to the communication problems arising in disconnected opportunistic vehicular networking scenarios. A new network architecture for vehicular communications is therefore proposed in this work, called vehicular delay-tolerant network (VDTN). Its layered structure is introduced and the corresponding performance analysis is conducted. This architecture differs from other proposals in the literature in several respects. Briefly, it adopts a store-carry-and-forward paradigm combined with an IP over VDTN approach and out-of-band signaling with control and data plane separation.

This thesis presents studies on the impact of stationary relay nodes, node density, vehicles movement patterns, and storage constraints on the VDTN network performance, in terms of bundle delivery probability and bundle average delivery delay. Of particular interest to this thesis is the performance improvement of these networks. In particular, node localization information is exploited to improve and optimize the use of data plane resources. It is demonstrated the performance gains attainable in a VDTN through the cooperation between network nodes, in terms of bundle delivery probability and bundle average delivery delay. These performance metrics are also used to investigate the impact of non-priority and priority-based queueing disciplines.

Finally, a detailed analysis is performed with the proposed routing protocol for VDTNs, called GeoSpray, against popular single-copy (Direct Delivery, First Contact, GeOpps), and multiple-copy (Epidemic, Spray and Wait, PRoPHET) routing protocols. Such protocols are considered reference in the literature of DTN networks and were deployed in VDTNs. It is shown that GeoSpray yields significant performance gains in terms of the bundle delivery probability and the bundle average delivery delay. The proposed protocol proves to be efficient in terms of storage and bandwidth resources utilization.

The results presented in this thesis are based on computer simulations and testbed experiments. The lack of a simulator specialized for VDTN layered network architecture, created the necessity to propose, develop, and implement a simulation tool for VDTNs, called VDTNsim. VDTNsim was used as a basis for the creation of a prototype of a VDTN laboratory testbed, named VDTN@Lab.

This thesis aims to contribute to the advance of the state-of-the-art on techniques for tackling the challenges that arise from the unique properties of vehicular networks. Further, this thesis highlights important guidelines for the improvement and design of new protocols, algorithms, services, and applications for vehicular delay-tolerant networks.

Keywords

Vehicular Delay-Tolerant Networking, Vehicular Ad-Hoc Networking, Vehicular Networking, Vehicular Communications, Delay and Disruption-Tolerant Networking, Opportunistic Networking, Routing, Cooperation, Queuing Disciplines, Scheduling Policies, Dropping Policies, Traffic Differentiation, Rural Connectivity, Geographic Localization, Simulation, Testbed, Performance Assessment

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Acronyms and Abbreviations

AHS	Advanced Cruise-Assist Highway Systems
AHSRA	Advanced Cruise-Assist Highway System Research Association
ARQ	Automatic Repeat-reQuest
BAD	Bundle Aggregation and De-aggregation layer
BSC	Bundle Signaling Control layer
C-ARQ	Cooperative ARQ
C2C	Car to Car
C2I	Car to Infrastructure
CB	Control Bundle
CONDOR	Command-Control, On-the-Move, Network, Digital, Over-the-horizon Relay
CoS	Classes of Service
CP	Contact Prediction algorithm
CST	Custom Service Time
CTP	Cabernet Transport Protocol
DARPA	Defense Advanced Research Projects Agency
DB	Data Bundle
DC-ARQ	Delayed Cooperative ARQ
DRIVE	DemonstRator for Intelligent Vehicular Environments
DSCP	Differentiated Services Code Point
DSRC	Dedicated Short Range Communications
DTN	Delay and Disruption Tolerant Network
DTNRG	DTN Research Group
ETA	Estimate the Time of Arrival
EUCAR	European Council for Automotive R&D
FIFO	First In, First Out
GB	Gigabyte
GIS	Geographic Information System
GPS	Global Positioning System
GUI	Graphical User Interface
ICT	Information Communities Technologies
IEEE	Institute of Electrical and Electronics Engineers
ILP	Integer Linear Programming
IP	Internet Protocol
IPN	Interplanetary networking
IRTF	Internet Research Task Force
ISO	International Organization for Standardization
IT	Instituto de Telecomunicações

ITS	Intelligent Transportation Systems
KB	Kilobyte
km/h	kilometre per hour
LIFO	Last In First Out
MAC	Media Access Control
MANET	Mobile Ad hoc NETwork
MB	Megabyte
MBM	random Map-Mased Movement
Mbps	Megabits per second
METD	Minimum Estimated Time of Delivery
MTU	Maximum Transmission Unit
N4C	Networking for Communications Challenged Communities
NETGNA	Next Generation Networks and Applications research group
NOW	Network On Wheels
NP	Nearest Point
OBS	Optical Burst Switching
ONE	Opportunistic Network Environment simulator
OSI	Open Systems Interconnection
PATH	California Partners for Advanced Transit and Highways
PDA	Portable Digital Assistant
PDU	Protocol Data Unit
PG	Priority Greedy
PHY	Physical
PoI	Point of Interest
PRECIOSA	Privacy Enabled Capability In Co-operative Systems and Safety Applications
QoS	Quality of Service
RC	Replicated Copies
RC ASC	Replicated Copies Ascending Order
RC DESC	Replicated Copies Descending Order
RFC	Request for Comments
RL	Remaining Lifetime
RL ASC	Remaining Lifetime Ascending Order
RL DESC	Remaining Lifetime Descending Order
RMBM	Routed Map-Based Movement
RSU	RoadSide infrastructure Units
RTT	Round-Trip Time
SNC	Saami Network Connectivity
SPMBM	Shortest Path Map-Based Movement
TCP	Transmission Control Protocol
TFT	Tit-For-Tat

TOS	Type Of Service
TTL	Time To Live
UBI	University of Beira Interior
UDP	User Datagram Protocol
UML	Unified Modeling Language
V2I	Vehicle-to-Infrastructure
V2R	Vehicle-to-Roadside
V2V	Vehicle-to-Vehicle
VANET	Vehicular Ad hoc NETwork
VDTN	Vehicular Delay-Tolerant Network
VSAT	Very Small Aperture Terminal
VTP	Vehicle Transmission Protocol
VWBS	Vehicular Wireless Burst Switching Network
WAVE	Wireless Access in Vehicular Environments
WLAN	Wireless Local Area Network
WSN	Wireless Sensor Network

Extended Abstract in Portuguese

O presente resumo alargado em língua portuguesa sintetiza a tese de Doutoramento intitulada "Avaliação do Desempenho de Redes Veiculares com Ligações Intermitentes" (*Performance Assessment of Vehicular Delay-Tolerant Networks*). Começa-se por enumerar os objectivos e referir as principais contribuições desta investigação. Depois são sintetizadas as principais conclusões e apontadas direcções para trabalho futuro.

Definição do Problema e Objectivos

As redes veiculares são definidas na literatura [1-3] como redes espontâneas e auto-organizadas, onde veículos equipados com dispositivos de comunicação sem fios de curto ou médio alcance, cooperam entre si para permitir a comunicação entre veículos e a comunicação entre veículos e outros equipamentos de infra-estrutura localizados junto às estradas. Os nós destas redes podem estar localizados em linha de vista ou fora do alcance de comunicação se for estabelecida uma rede através de múltiplos saltos entre diversos nós.

Em termos de investigação, constata-se que os primeiros esforços na área das redes veiculares remontam aos anos 80 [4]. No entanto, esta área de investigação foi impulsionada por volta do ano de 2000 com o desenvolvimento das tecnologias de comunicação sem fios [5]. Recentemente, tem-se vindo a evidenciar um forte contributo e interesse nesta área por parte de governos, da indústria e de comunidades de investigação. Os fabricantes de automóveis estão já a trabalhar no desenvolvimento de protótipos de veículos dotados de sistemas computacionais, sensores, e interfaces de comunicação sem fios [6-8]. Assim, prevê-se que as redes veiculares virão muito provavelmente a ser implementadas num futuro próximo.

Uma das razões principais para o crescente interesse nestas redes está relacionada com a sua potencial utilização numa ampla gama de aplicações com impacto na vida quotidiana [1, 9], das quais se destacam, entre muitas outras, as seguintes. As redes veiculares são consideradas uma tecnologia fundamental para a melhoria da segurança rodoviária, podendo ajudar os condutores a evitar acidentes, ou evitar colisões em cadeia após a ocorrência de um acidente. A comunicação veicular pode ser de grande utilidade na melhoria da eficiência dos sistemas de transporte, podendo contribuir para optimizar os fluxos de tráfego e a capacidade das estradas. As redes veiculares também podem ser utilizadas para recolher e transmitir os dados capturados por uma rede de sensores sem fios, por exemplo referentes a condições climatéricas ou medições de poluição. Outros exemplos de aplicações previstas para estas redes, incluem aplicações comerciais (p. ex. para divulgação de anúncios, de informações turísticas e de lazer, e disponibilidade de espaço de estacionamento) e aplicações de entretenimento (p. ex. permitindo o acesso à Internet e partilha de conteúdos de multimédia). As redes veiculares poderão ser particularmente importantes em regiões remotas ou comunidades rurais em países subdesenvolvidos, que não dispõem de qualquer tipo de meio de comunicação convencional de acesso à Internet, permitindo um conjunto diversificado de serviços (p. ex. transferência de ficheiros, correio electrónico, acesso à Web baseado em mecanismos de cache e aplicações de telemedicina e monitorização à distância). Estas redes podem ainda revelar-se muito úteis num cenário de catástrofe natural (p. ex. um terramoto, inundação ou incêndio), quando as infra-estruturas de rede tradicionais são destruídas ou largamente afectadas, permitindo apoiar a comunicação entre equipas de resgate e outros serviços de emergência.

No entanto, para que estas aplicações se tornem uma realidade, é fundamental encontrar soluções para uma série de inúmeros problemas e desafios técnicos que caracterizam estas redes. Alguns desses desafios são comuns a outras redes sem fios, enquanto outros são colocados pelas características particulares das redes veiculares. De acordo com [2, 3, 10-12], a maioria dos problemas é causada pela mobilidade e a velocidade dos veículos, a qual é responsável por uma topologia de rede altamente dinâmica e tempos de contacto entre nós da rede de duração reduzida. A estes problemas acrescentam-se as limitações no alcance da transmissão, os problemas de propagação causados por obstáculos (tais como edifícios, túneis, terreno e vegetação) e as interferências. Em conjunto, estes problemas tornam estas redes susceptíveis a problemas de conectividade intermitente e divisão/partição da rede, resultando na impossibilidade frequente de estabelecer uma ligação extremo-a-extremo entre a origem e o destino para a comunicação de dados. Além disso, destaca-se que a densidade de nós nestas redes pode ser altamente variável. Por exemplo, uma rede veicular pode ser classificada como sendo densa num engarrafamento, enquanto que no tráfego suburbano pode ser esparsa, ou até mesmo extremamente esparsa em zonas rurais/remotas.

Dada a grande abrangência dos tópicos de investigação nestas redes, considerou-se adequado focar a investigação apresentada nesta tese nas questões inerentes à disseminação de dados e encaminhamento de dados. Estes tópicos haviam merecido uma atenção considerável por parte da comunidade científica à data de inicio desta investigação, Setembro de 2007. No entanto, a maioria dos estudos publicados considerava habitualmente cenários de auto-estradas e ruas citadinas, caracterizados por uma alta densidade de nós ou até mesmo redes totalmente conectadas. Os protocolos de encaminhamento propostos na literatura para estas redes, designadas de redes veiculares ad-hoc (*vehicular ad-hoc networks* (VANET)) [1-3, 9, 13-15], assumem a existência de uma ligação extremo-a-extremo entre o emissor e o receptor de dados [16, 17]. Desta forma, estes protocolos apresentam como grande limitação a incapacidade de lidar com ligações intermitentes, com a frequente desconexão da rede (partições da rede) e atrasos longos ou variáveis [2], [3], [18], [19], [20]. Tais situações são muito comuns em cenários urbanos ou rurais caracterizados por densidades de nós moderadas ou reduzidas, e pouca ou nenhuma infra-estrutura de rede fixa disponível.

A arquitectura de rede proposta para redes com ligações intermitentes, ditas *delay/disruption-tolerant networks* (DTN) [21], e inicialmente aplicada às redes interplanetárias, foi entretanto considerada como uma solução para resolver estes problemas, dando origem a uma nova abordagem para as redes veiculares designada por redes veiculares ad-hoc baseadas em DTNs [10, 11, 22-26]. A arquitectura DTN propõe a introdução de uma camada protocolar, sobre a camada de "transporte", segundo o modelo de referência OSI [27, 28], designada por camada de "agregação" ("*bundle layer*"). Esta camada pretende criar uma rede "*overlay*", permitindo a interligação de redes altamente heterogéneas (p. ex. uma rede interplanetária ou uma rede de sensores) através de um paradigma de comutação assíncrona de mensagens. Segundo este paradigma, as mensagens também designadas por agregados ("*bundles*") são armazenadas (em memória persistente) e enviadas assincronamente nó a nó, desde a origem até o destino [29]. Considera-se que as mensagens têm tamanho variável e representam agregados de dados vindos da camada de "aplicação", segundo o modelo de referência OSI.

A arquitectura DTN oferece uma solução promissora para melhorar o desempenho do encaminhamento e da disseminação de dados em redes veiculares desconectadas/intermitentes e oportunísticas, a qual tem recebido uma atenção crescente nos últimos anos. A utilização deste paradigma permite que o tráfego de dados de uma variedade de aplicações veiculares tolerantes ao atraso e à perda de alguns dados, seja encaminhado ao longo do tempo, explorando-se o movimento físico dos veículos e os contactos oportunísticos estabelecidos entre estes e com outros nós da rede.

Contudo, esta solução afasta-se do modelo Internet caracterizado pela utilização do protocolo Internet (IP) [30] extremo-a-extremo em vez do "*bundling*" das DTNs [31]. Os benefícios de manter a semântica de comunicação IP extremo-a-extremo são evidentes, uma vez que facilita a interoperabilidade com as redes existentes e com algumas aplicações da Internet. Além disso, não são necessários *gateways* de conversão protocolar. Pode ainda observar-se que o IP em si oferece um mecanismo de entrega assíncrona de datagramas, e que a entrega de datagramas IP pode ser adiada se as aplicações envolvidas tolerarem atrasos elevados e comunicações assíncronas [32]. Desta forma, poderá combinar-se a utilização de protocolos UDP [33] ou baseados em UDP nas camadas superiores, com a resolução das questões inerentes à intermitência e desconexão abaixo da camada de "rede" segundo o modelo de referência OSI.

O trabalho apresentado nesta tese é motivado pela necessidade de encontrar novas soluções para os problemas de comunicação decorrentes de cenários de redes veiculares desconectadas/intermitentes e oportunísticas. O principal objectivo deste trabalho é apresentar a proposta de uma nova arquitectura de camadas para redes veiculares, designadas de redes veiculares com ligações intermitentes, ditas *vehicular delay-tolerant networks* (VDTN), incluindo a definição dos elementos/nós da rede. Para além disso, apresenta-se um estudo do desempenho desta arquitectura de rede e respectivos protocolos, algoritmos e serviços, analisando-se a sua aplicação em diferentes cenários.

Para atingir este objectivo principal, foram identificados os seguintes objectivos intermédios:

- Proposta de uma arquitectura de camadas para redes veiculares, designadas de redes veiculares com ligações intermitentes (ditas *vehicular delay-tolerant networks* (VDTN)), compostas por diferentes tipos de nós com funções e capacidades distintas;
- Proposta e criação de uma ferramenta de simulação para redes VDTN para apoio ao desenvolvimento, experimentação e avaliação de desempenho de protocolos, algoritmos e serviços;
- Proposta e construção de um protótipo (ou demonstrador) laboratorial para redes VDTN para demonstrar estas redes e verificar experimentalmente as melhores soluções obtidas nos estudos realizados por simulação, ficando também disponível para permitir a realização de novos estudos;
- Estudo do impacto dos nós fixos de *relay*, da densidade de nós e dos modelos de mobilidade, e das restrições de armazenamento, no desempenho de protocolos de encaminhamento populares em redes DTN (Epidemic, Spray and Wait, PRoPHET, e MaxProp) aplicados a VDTNs;
- Estudo do impacto da utilização de informação de localização de nós no desempenho das redes VDTN;
- Estudo do efeito do nível de cooperação dos nós no desempenho das redes VDTN;
- Estudo do impacto de politicas de escalonamento e de politicas de descarte, com base ou não em prioridades, no desempenho das redes VDTN;
- Proposta e estudo do desempenho de um novo protocolo de encaminhamento para redes VDTN.

Principais Contribuições

Esta secção é dedicada às principais contribuições científicas da presente tese. Neste sentido, os próximos parágrafos descrevem, na opinião do autor, as principais contribuições para o avanço do estado da arte na área das redes veiculares com ligações intermitentes.

A primeira contribuição desta tese é uma análise detalhada e compreensiva do estado da arte relacionado com as redes veiculares e as redes com ligações intermitentes (redes DTN), a qual é apresentada no Capítulo 2. Uma versão resumida desta análise foi apresentada na *10ª*

Conferência sobre Redes de Computadores (CRC 2010) [34]. Um artigo de análise com uma visão e discussão das abordagens actuais e mais representativas às redes veiculares e dos desafios identificados nesta área de investigação foi aceite para publicação na revista *IEEE Communications Surveys & Tutorials Journal* [35].

A segunda contribuição é a proposta inovadora de uma arquitectura organizada em camadas para redes veiculares com ligações intermitentes (*vehicular delay-tolerant networks* (VDTN)), baseada nos seguintes princípios: *i)* comunicação orientada à transmissão de agregados de datagramas; *ii)* paradigma baseado no "armazenamento, transporte e envio de agregados"; e *iii)* separação do plano de controlo e do plano de dados, utilizando sinalização fora-de-banda ("*out-of-band signaling*"). Esta proposta é apresentada na Secção 3.2. Uma proposta inicial com vista à especificação da arquitectura VDTN foi apresentada no *3rd IEEE Workshop on Automotive Networking and Applications (Autonet 2008)*, que fez parte da *IEEE GLOBECOM 2008* [36]. A proposta da arquitectura de camadas VDTN foi apresentada no *Fourteenth IEEE Symposium on Computers and Communications (ISCC 2009)* [37]. Estes trabalhos conduziram a um pedido de patente Portuguesa para a arquitectura VDTN e respectivo método de transmissão de dados. Este pedido de patente intitula-se "Método de transmissão de dados em redes veiculares com ligações intermitentes" [38] e foi publicado em 27 de Outubro de 2010. Considera-se também relevante, neste contexto, a publicação dos principais resultados do *NoE Euro-NF Specific Joint Research Project VDTN*, apresentada na *7th Euro-NF Conference on Next Generation Internet (NGI 2011)* [39].

A terceira contribuição é a proposta e implementação de uma ferramenta de simulação para redes veiculares com ligações intermitentes, denominada VDTNsim, que é descrita na Secção 4.2. Esta ferramenta de simulação foi apresentada no *15th IEEE International Workshop on Computer-Aided Modeling Analysis and Design of Communication Links and Networks (IEEE CAMAD 2010)* [40].

A quarta contribuição é a proposta e implementação de uma *testbed* laboratorial para redes veiculares com ligações intermitentes, designada VDTN@Lab, a qual é apresentada na Secção 4.3. Uma versão preliminar deste protótipo foi apresentada na *5.ª Conferência de Engenharia (Engenharia'2009) - Inovação e Desenvolvimento* [41]. Uma versão mais avançada da *testbed* foi utilizada num conjunto de estudos subsequentes apresentados na *8th Conference on Telecommunications (CONFTELE 2011)* [42], na *2011 IEEE International Conference on Communications (IEEE ICC 2011)* [43], e na *16th IEEE International Workshop on Computer Aided Modeling Analysis and Design of Communication Links and Networks (IEEE CAMAD 2011)* [44].

A quinta contribuição é um estudo do impacto dos nós fixos de *relay* no desempenho de protocolos de encaminhamento populares em redes DTN aplicados a VDTNs, o qual é apresentado na Secção 5.3. Um primeiro estudo para avaliação de desempenho, considerando apenas um cenário de conectividade urbana, foi apresentado na *5th Euro-NGI Conference on Next Generation Internet Networks (NGI 2009)* [45]. Uma versão estendida deste trabalho, apresentando estudos que consideram cenários de conectividade urbana e rural com áreas de diferentes dimensões, diferentes densidades de nós e modelos de mobilidade, foi publicado como capítulo do livro *Mobile Opportunistic Networks: Architectures, Protocols and Applications* [46], publicado pela *CRC Press – Taylor & Francis Group*.

A sexta contribuição é uma análise da influência dos modelos de mobilidade e da densidade do número de nós móveis (veículos) no desempenho de protocolos de encaminhamento populares em redes DTN aplicados a uma rede VDTN num cenário de conectividade rural, a qual é apresentada na Secção 5.4. Uma versão preliminar deste estudo foi apresentada na *7th Conference on Telecommunications (CONFTELE 2009)* [47]. Uma versão estendida deste trabalho foi seleccionado para publicação na revista *International Journal of Mobile Network Design and Innovation (IJMNDI), Inderscience Publishers* [48]. Esta versão estendida considerou diferentes modelos de mobilidade e diferentes densidades de nós, e analisou a variação dos parâmetros dos protocolos de encaminhamento com o objectivo de determinar o seu impacto no desempenho da rede.

A sétima contribuição é um estudo que avalia o efeito causado pelas restrições ao nível da capacidade de armazenamento dos nós da rede, no desempenho de redes veiculares com ligações intermitentes. Este estudo, descrito na Secção 5.5, foi apresentado na *Second International Conference on Communication Theory, Reliability, and Quality of Service (CTRQ 2009)* [49]. Este trabalho recebeu o prémio de melhor artigo ("*best paper award*") na conferência.

A oitava contribuição é um estudo que analisa a utilização de informação de localização dos nós para prever a duração do tempo de contacto, por forma a melhorar o desempenho das redes VDTN. Este estudo, exposto na Secção 3.3 e avaliado na Secção 6.3, foi apresentado na *2010 IEEE International Conference on Communications (IEEE ICC 2010)* [50].

A nona contribuição é uma análise da influência da cooperação dos nós da rede no desempenho de redes veiculares com ligações intermitentes, a qual é apresentada na Secção 6.4. Este trabalho foi seleccionado para publicação como capítulo do livro *Cooperative Networking* [51], publicado pela *Wiley*.

A décima contribuição é uma análise do impacto das politicas de escalonamento e das politicas de descarte no desempenho das redes VDTN, a qual é apresentada na Secção 6.5. Uma versão preliminar deste estudo foi apresentado no *Second International Workshop on Next Generation of Wireless and Mobile Networks (NGWMN-09)*, que fez parte da *38th International Conference on Parallel Processing (ICPP-2009)* [52]. Uma versão estendida deste artigo foi publicada na revista *International Journal On Advances in Internet*

Technology, IARIA [53]. Esta versão estendida teve em conta um conjunto alargado de politicas de escalonamento e de politicas de descarte, as quais foram avaliadas em cenários com diferentes densidades de nós móveis movendo-se a diferentes velocidades.

A décima primeira contribuição é um estudo da problemática do suporte de diferenciação de tráfego em redes VDTN, o qual é apresentado na Secção 3.4 e avaliado na Secção 6.6. Uma versão preliminar deste estudo foi apresentado na *17th International Conference on Software, Telecommunications and Computer Networks (SoftCOM 2009)* [54]. Uma versão estendida deste trabalho foi aceite para publicação na revista *Telecommunication Systems Journal, Springer* [55]. Esta versão estendida teve em conta um conjunto alargado de mecanismos necessários à diferenciação de tráfego, nomeadamente, estratégias de gestão de buffers, politicas de escalonamento e de politicas de descarte. O desempenho destes mecanismos foi avaliado em cenários com diferentes densidades de nós móveis movendo-se a diferentes velocidades.

A décima segunda contribuição é a proposta, especificação e avaliação do desempenho de um novo protocolo de encaminhamento geográfico para redes VDTN, intitulado de GeoSpray, que é apresentado na Secção 3.5 e avaliado na Secção 6.7. Esta contribuição foi aceite para publicação na revista *Information Fusion Journal, Elsevier* [56].

Conclusões e Sugestões para Trabalho Futuro

Ao longo da presente tese foi estudado o desempenho de redes veiculares com ligações intermitentes (redes VDTN). Este ponto apresenta uma síntese da tese e aponta algumas direcções para trabalho futuro.

Após a apresentação e delimitação do tema da tese, descrevendo-se os seus objectivos e as suas principais contribuições, foram descritos os principais aspectos das redes veiculares e das redes com ligações intermitentes (redes DTN). Neste ponto começou-se por apresentar um sumário das principais aplicações das redes veiculares e de projectos de investigação relacionados com estas redes. Depois, o trabalho centrou-se na apresentação da arquitectura/tecnologia das redes veiculares ad-hoc, ditas vehicular ad-hoc networks (VANET), prestando-se especial atenção à discussão das limitações das estratégias usuais de disseminação de dados e de encaminhamento propostas na literatura para estas redes. Estas limitações motivaram a introdução dos conceitos da arquitectura de rede proposta para redes com ligações intermitentes nas redes VANET. No que diz respeito às DTNs, foi descrita a arquitectura proposta para estas redes. Vários tópicos de investigação em DTNs foram também apresentados e discutidos, nomeadamente, cenários de aplicação, protocolos de encaminhamento, nós fixos de *relay*, cooperação e disciplinas de filas (politicas de escalonamento e politicas de descarte).

Em seguida, foi apresentada a proposta de uma arquitectura organizada em camadas para comunicações veiculares em redes esparsas/particionadas e oportunisticas, designadas de redes veiculares com ligações intermitentes (redes VDTN). A arquitectura de rede VDTN apenas partilha em comum com a arquitectura DTN a assumpção de comunicação de dados assíncrona, baseada no paradigma de "armazenamento, transporte e envio de mensagens". Porém, distancia-se da abordagem muito abrangente da arquitectura DTN, posicionando a camada de "agregação" entre a camada de "rede" e a camada de "ligação de dados" segundo o modelo de referência OSI. Desta forma, os datagramas (p. ex. pacotes do Internet protocol - IP) com características comuns (p. ex. mesmo destinatário) são agrupados numa unidade protocolar de dados designada também de "agregado" ("*bundle*"). A arquitectura VDTN também introduz o conceito de separação entre o plano de controlo e o plano de dados, com recurso a sinalização fora-de-banda ("*out-of-band signaling*"). Este conceito, permite que o método de transmissão de dados utilizado nas redes VDTN, utilize um conjunto de mensagens de sinalização enviadas *a priori* (no plano de controlo), para efectuar a reserva de recursos disponíveis nos nós da rede para a (eventual) posterior transmissão dos agregados (no plano de dados). Inclusivamente, é possível utilizar diferentes tecnologias de transmissão de dados para cada um dos planos. Neste ponto, foram definidas as camadas propostas pela arquitectura VDTN e foram descritas e discutidas as características dos protocolos a implementar em cada uma delas.

Depois, foi apresentada a proposta de um novo protocolo de encaminhamento geográfico para redes VDTN, designado por GeoSpray. Este protocolo de encaminhamento é baseado nos seguintes princípios: *i)* suporte a um paradigma de rede oportunística e entrega de agregados com base no paradigma de "armazenamento, transporte e envio de agregados"; *ii)* utilização de informação de localização geográfica disponibilizada por dispositivos para obtenção de posição, para auxiliar na tomada de decisões de encaminhamento; *iii)* utilização de um esquema de encaminhamento multi-cópia com um limite estrito no número de cópias criado por agregado, combinado com uma estratégia de *forwarding* com vista a melhorar a probabilidade de entrega dos agregados via rotas multi-salto; *iv)* libertação de espaço em *buffer*, relativo aos agregados que já foram entregues; *v)* optimização dos recursos utilizados na rede, incluindo armazenamento, largura de banda e energia; e *vi)* maximizar a probabilidade de entrega de agregados, minimizar o atraso na entrega de agregados e sobrecarga de recursos ("*overhead*").

Dadas as particularidades da arquitectura de rede VDTN, tornou-se necessário desenvolver uma ferramenta de simulação, designada por VDTNsim, para suportar trabalhos de investigação relacionados com o desenvolvimento, experimentação e avaliação de desempenho de protocolos, algoritmos e serviços para estas redes. Esta ferramenta foi utilizada em todos os estudos de simulação apresentados nesta tese. Apresentou-se ainda uma *testbed* laboratorial (protótipo) para redes VDTN, designada por VDTN@Lab. Esta *testbed* pretende proporcionar um meio para entender a interacção com um ambiente real (emulado), bem como para a validação de modelos de simulação. A *testbed* foi utilizada para realizar uma série de experiências também apresentadas na parte final desta tese.

De seguida, foram apresentados um conjunto de projectos que têm vindo a utilizar os conceitos e técnicas associadas à arquitectura DTN, para suportar um conjunto diversificado de serviços que não têm características de tempo real, em regiões remotas, ou comunidades rurais em países subdesenvolvidos. Indicou-se um exemplo de como uma rede VDTN pode ser utilizada neste tipo de cenário, e foram realizadas um conjunto de simulações sobre o mesmo. Assumiu-se a utilização dos quatro protocolos de encaminhamento mais relevantes propostos na literatura para redes baseadas no conceito DTN: Epidemic, Spray and Wait, MaxProp e PRoPHET. Começou-se por avaliar o impacto dos nós fixos de *relay* em cenários caracterizados por elevadas dimensões, densidades de nós reduzidas e poucas oportunidades de contactos. Foi demonstrado que estes nós têm um papel fundamental mesmo em redes oportunísticas, contribuindo para aumentar o número de oportunidades de contacto significativamente. Consequentemente, verificou-se que aumentam a probabilidade de entrega de agregados e reduzem o tempo médio do atraso na entrega de agregados de todos os protocolos de encaminhamento estudados, com um efeito ligeiramente mais pronunciado no protocolo MaxProp.

Também foi estudada a influência da densidade dos nós móveis e de diferentes modelos de mobilidade, no número de oportunidades de contacto e por conseguinte na probabilidade de entrega de agregados e no tempo médio do atraso na entrega de agregados dos mesmos protocolos de encaminhamento, bem como o impacto dos parâmetros de configuração dos protocolos Spray and Wait e PRoPHET no desempenho dos mesmos. Depois, foi analisado o impacto causado pela introdução de restrições de espaço de armazenamento em diferentes nós da rede, na probabilidade de entrega de agregados dos mesmos protocolos de encaminhamento. Verificou-se que as diferentes estratégias de replicação de agregados destes protocolos, reagem de forma distinta ao aumento do espaço de armazenamento em tipos de nós específicos. Por exemplo, os protocolos Epidemic e MaxProp tiram partido do aumento do espaço de armazenamento em todos os nós da rede, enquanto que o protocolo Spray and Wait apenas aumenta a sua probabilidade de entrega se a capacidade de armazenamento disponível nos nós móveis (veículos) for aumentada.

Em seguida, foram estudadas várias técnicas que têm um papel determinante na melhoria do desempenho das redes veiculares com ligações intermitentes. Começou-se por explorar as características da separação do plano de controlo e do plano de dados com utilização de sinalização fora-de-banda, para introduzir a função de localização de nó no plano de controlo. Discutiu-se como esta funcionalidade pode ser utilizada para prever a duração do tempo de contacto e o número máximo de bytes que podem ser transmitidos. Verificou-se que a informação acerca da duração do contacto permite também determinar o período de tempo durante o qual se deve activar a ligação utilizada no plano de dados, o que permite estender o tempo de duração da bateria dos nós com restrições energéticas, tais como os nós fixos de *relay*. Os resultados dos estudos apresentados mostram que esta abordagem permite prevenir transmissões de agregados incompletos, aumentando assim o número de agregados transmitidos com sucesso. Esta optimização da utilização dos recursos da ligação do plano de dados, resultou numa melhoria considerável da probabilidade de entrega de agregados e na redução do tempo médio do atraso na entrega de agregados.

Depois, analisou-se de que forma a falta de cooperação entre nós da rede pode afectar a funcionalidade das redes VDTN. Os estudos realizados visavam avaliar o impacto da cooperação ao nível plano de dados. A partir da análise dos resultados, observou-se que o comportamento não-cooperativo afecta de forma drástica a probabilidade de entrega de agregados e o tempo médio do atraso na entrega de agregados para os protocolos de encaminhamento Epidemic e Spray and Wait, com um efeito mais pronunciado no segundo. Este estudo abre caminho para futuras investigações sobre mecanismos que incentivem a cooperação entre os nós da rede VDTN.

Estudaram-se também as implicações das politicas de escalonamento e das politicas de descarte no desempenho das redes VDTN, em termos de probabilidade de entrega de agregados e tempo médio do atraso na entrega de agregados. Uma análise comparativa de diversas politicas revelou a importância de combinar uma politica de escalonamento e uma politica de descarte que dêem tratamento preferencial aos agregados menos replicados na rede. Concluiu-se que esta combinação de politicas resulta num desempenho muito superior, em ambas as métricas, quando comparada à tradicional política FIFO ("*first in, first out*") com descarte na cabeça da fila ("*head-drop*").

Também foi estudada a implementação de diferenciação de tráfego em redes VDTN, baseada em classes de serviço. O estudo centrou-se na análise de como diferentes estratégias de gestão de buffers podem ser combinadas com politicas de descarte e politicas de escalonamento, para disponibilizar serviços baseados em prioridades estritas ou em alocação de recursos. Apresentou-se uma avaliação de desempenho destas propostas. Este estudo confirmou a importância do suporte de diferenciação de tráfego nestas redes e abre caminho para futuras investigações neste tópico.

De seguida, foi efectuada a avaliação do desempenho do protocolo GeoSpray em comparação com o desempenho dos seguintes protocolos de encaminhamento propostos na literatura para redes DTN: First Contact, Direct Delivery, Epidemic, Binary and Source Spray and Wait, PRoPHET e GeOpps. Foram consideradas as seguintes métricas de desempenho neste estudo: probabilidade de entrega de agregados, tempo médio do atraso na entrega de agregados, número de transmissões iniciadas de agregados, número de agregados descartados, sobrecarga de recursos ("*overhead*"), número de saltos médio, e tempo médio em buffer. Os protocolos foram avaliados em cenários com diferentes densidades de nós. Observou-se que o GeoSpray melhora significativamente a probabilidade de entrega de agregados e reduz o tempo médio do atraso na entrega de agregados, quando comparado com os outros protocolos de encaminhamento. Além disso, apresenta uma baixa taxa de agregados descartados e um baixo *overhead*. Desta forma, considera-se que o protocolo proposto é eficiente em termos da utilização dos recursos de armazenamento e largura de banda.

Finalmente, foi apresentado um estudo experimental realizado com recurso à *testbed* laboratorial VDTN@Lab, que visa avaliar e comparar o desempenho dos protocolos de encaminhamento First Contact, Direct Delivery, Epidemic, Spray and Wait e PRoPHET numa rede VDTN. As métricas de desempenho consideradas neste estudo incluíram a probabilidade de entrega de agregados, o tempo médio do atraso na entrega de agregados e o número de agregados descartados. Verificou-se que o protocolo Spray and Wait apresenta um desempenho muito superior quando comparado com os restantes protocolos de encaminhamento, o que confirma os resultados observados nos estudos de simulação apresentados nesta tese.

De uma forma global, os resultados apresentados nesta tese fornecem um número de contribuições consideradas relevantes no âmbito do desenvolvimento das futuras redes veiculares.

Sugestões para Trabalho Futuro

Ao terminar esta tese, resta sugerir futuros temas de investigação resultantes do trabalho de investigação desenvolvido:

- Propor e avaliar mecanismos de incentivo à cooperação em redes VDTN.
- Introduzir mecanismos para suporte de qualidade de serviço no protocolo de encaminhamento GeoSpray, e estudar o seu efeito sobre o tráfego da rede e a utilização de recursos da rede.
- Estudar, implementar e avaliar algoritmos/políticas de agregação de *bundles* de dados.
- Estudar, implementar e avaliar algoritmos de controlo de fluxo e de controlo de congestão.
- Estudar o efeito da fragmentação proactiva e reactiva no desempenho dos protocolos de encaminhamento estudados nesta tese.
- Extender a *testbed* laboratorial (VDTN@Lab), introduzindo novas funcionalidades.
- Implementar e avaliar as propostas apresentadas nesta tese na *testbed* laboratorial, comparando com os resultados obtidos por simulação.
- Criar uma *testbed* real para implementação, demonstração e avaliação do desempenho dos serviços, protocolos e aplicações VDTN em ambiente real. Esta

testbed real será utilizada para comprovar os resultados já obtidos por simulação e na *testbed* laboratorial. Um esforço para alcançar este objectivo já foi iniciado, com a apresentação de uma *testbed* real que demonstra e valida os conceitos técnicos da arquitectura VDTN em ambiente real [57].

Por último, pretende-se disponibilizar à comunidade científica a ferramenta de simulação (VDTNsim), o modelo baseado no mapa da região da Serra da Estrela, e o software que é executado na *testbed* laboratorial (VDTN@Lab). Os mesmos estarão disponíveis no sítio Web do grupo de investigação NetGNA [58].

Chapter 1

Introduction

1.1. Focus

Vehicular networks have been defined in the literature [1-3] as spontaneous self-organized networks, where vehicles equipped with short to medium range wireless communication capabilities cooperate with each other to enable communication with other vehicles or roadside infrastructure equipment. In these networks, nodes can be located in line of sight or out of the radio range if a multihop network is built among several nodes.

Although research in vehicular networks dates back to the 80's [4] the field exploded around the year 2000 with the development of adequate and affordable wireless communication technologies [5]. Recently, these networks are attracting much attention from governments, industry, and academic research communities all over the world. In fact, many automobile manufacturers are already developing prototypes of vehicles equipped with sensing, computing and wireless communication devices [6-8]. Hence, it is envisioned that vehicular networks are very likely to be deployed in the coming years.

One of the main reasons, if not the most important, for the growing interest in these networks is the wide range of envisioned applications that can have a direct impact on everyday life [1, 9], from time critical applications to delay tolerant applications. These networks are regarded as a key technology for improving road safety, optimizing the traffic flow and road capacity. They can also be used as monitoring networks for sensor data collection. Several commercial (e.g., commercial advertisements and parking space availability) and entertainment applications (e.g., Internet access and multimedia content sharing) have been envisioned. Vehicular networks can also be employed to provide connectivity to remote rural communities and regions, or to assist communication between rescue teams and other emergency services in catastrophe hit areas lacking a conventional communication infrastructure.

However, in order to harness the advantages of vehicular networks, a number of technical challenges need to be overcome before these networks can be widely deployed. Some of these challenges are common to other wireless networks, while others are caused by the unique properties of vehicular networks. According to [2, 3, 10-12], most of the problems arise from the mobility and speed of vehicles that are responsible for a highly dynamic network topology and short contact durations. It is interesting to notice that a driver might adjust his/her behavior to the data received from the network, thus inflicting a topology change. Limited transmission ranges, radio obstacles due to physical factors (e.g., buildings, tunnels, terrain and vegetation), and interferences (i.e., high congestion channels caused by high density of nodes), lead to disruption, intermittent connectivity, and significant loss rates. All these conditions make vehicular networks subject to frequent fragmentation/partition (i.e., end-to-end connectivity may not exist), resulting in small effective network diameter. Furthermore, vehicular networks have the potential to grow to a large-scale, and its node density, which is affected by location and time, can be highly variable. For example, a vehicular network can be categorized as being dense in a traffic jam, whereas in suburban traffic it can be sparse. In fact, in rural areas, the network can be extremely sparse.

Despite recent advances in vehicular networking, many research challenges remain in different areas, such as, wireless access technologies, spectrum issues, power management, data dissemination, routing, quality of service, security and privacy, applications and services, modeling and simulation, and field trials and deployments. The following is a brief description of these areas.

The research in wireless access technologies focuses on creating standards for high-speed vehicular communications, which exploit the limited radio spectrum allocated by standardization bodies. Although vehicles can generate sufficient electric power to feed a communications system and a powerful computer, fixed network nodes may have power constraints. Hence, optimizing energy consumption for these nodes is also a topic of interest. Furthermore, even though high transmission power is desirable to maximize throughput, it may cause interferences and disruption in a dense network. This is another research issue.

The design of routing protocols and data dissemination strategies is a major challenge. Routing protocols are responsible for the selection of paths from a source to a destination or destinations, which is considered a challenging task due to the unique networking properties of these networks. For example, conventional ad hoc routing protocols have been shown to be inadequate for vehicular networks. Quality of service, which is used to express the level of performance provided to applications, is considered a challenging topic. The dynamic mobile and ad-hoc nature of vehicular environments does not allow the adoption of resource reservation techniques used in traditional networked environments.

Security topic addresses research issues related to trust, resiliency, and efficiency. Issues related to privacy must also be addressed effectively, because anonymity must be preserved. The diversity of services and applications with different requirements and constraints also raises interesting research problems. Moreover, operation details are not yet standardized for most applications.

Simulation involves the development of models that represent the network (including protocols, algorithms, services, layering and architecture), applications, and vehicular traffic mobility and driver behavior in different environments (e.g., urban, suburban, rural), to support research activities. Field trials and deployments have an important role in the verification of the architectures, services, protocols, and applications developed for vehicular networks, and therefore attract much research interest.

All these areas of investigation are important and challenging because of their complexity. Nevertheless, the research performed within the scope of this thesis focuses on the inherent problems in data dissemination and routing in sparse or partitioned opportunistic vehicular networks. Hence, the remaining areas are considered beyond the scope of this work and left for future research.

1.2. Problem Definition and Objectives

At the starting point of this research program, in September of 2007, considerable attention had been given to vehicular communications. However, most of the published studies typically addressed the data dissemination and routing problems on highways and city road scenarios characterized by high node densities or even in fully connected networks. Only a few works provided solutions for routing in sparse or partitioned opportunistic vehicular networks, where the node density is not high enough to establish end-to-end links. To do so, the store-carry-and-forward paradigm of delay/disruption-tolerant networks (DTNs) [21] was incorporated in vehicular networks [10, 11, 22]. This paradigm allows delay-tolerant data traffic from a variety of vehicular applications to be routed over time, exploiting the physical movement of vehicles and the opportunistic links they establish with each other and with other network nodes.

The DTN architecture can be described as an overlay network that operates over different transport and lower layer protocols of heterogeneous networks deployed in extreme environments, where the basic assumptions of TCP/IP stack [59] do not hold true. This approach allows using optimized network stacks to tackle the characteristics of different networks, like an interplanetary network or a sensor network, and interconnecting them using asynchronous message switching. The DTN architecture offers a promising solution for improving the performance of routing and data dissemination in sparse or partitioned opportunistic vehicular networks that has received increasing attention. Nevertheless, this architecture departs from the Internet model that is defined by the end-to-end use of the Internet protocol (IP) [30] rather than bundling [31]. In addition, it can be observed that IP itself provides asynchronous packet delivery mechanism and IP packet delivery can be delayed if applications tolerate large delays and asynchronous communications.

These observations motivate the proposal of a new network architecture for sparse or partitioned opportunistic vehicular networks. Therefore, the main objective of this thesis is to present the proposal of a vehicular delay-tolerant network (VDTN) architecture, including the definition of its network elements. Furthermore, performance evaluation studies of this network architecture and related protocols, algorithms, and services, analyzing their applicability in different scenarios are needed.

To reach this main objective, the following intermediate objectives were identified:

- Proposal of a layered network architecture, named vehicular delay-tolerant network (VDTN), for data relaying in sparse or partitioned opportunistic vehicular networks, composed by distinct types of nodes with different roles and capabilities;
- Proposal and creation of a simulation tool for VDTN networks to support research studies related with the development, experimentation, and performance evaluation of protocols, algorithms, and services;
- Proposal and construction of a laboratory testbed (prototype) for VDTN networks for demonstration and experimental verification of the best solutions obtained by simulation. The testbed will be left available to enable further performance assessment studies;
- Performance evaluation of the impact of stationary relay nodes, node density and mobility models, and storage constraints on the popular routing protocols for DTN-based networks (Epidemic, Spray and Wait, PRoPHET, and MaxProp) applied to VDTNs;
- Performance study of the impact of using node localization information in VDTN networks;
- Performance analysis of the effect of node cooperation level in VDTN networks;
- Performance study of non-priority and priority-based queueing disciplines in VDTN networks;
- Proposal and performance assessment study of a new routing protocol for VDTN networks.

1.3. Main Contributions

This Section is devoted to the main scientific contributions of this thesis. Thus, the following paragraphs describe, in the opinion of the author, the main contributions for the advance of the state-of-art in the area of vehicular delay-tolerant networks.

The first contribution of this thesis is a detailed and comprehensive analysis of the state of the art related with vehicular communications and delay-tolerant networking, which is presented in Chapter 2. A preliminary version of this analysis was presented at the *10ª Conferência sobre Redes de Computadores (CRC 2010)* [34]. A survey providing an overview and a discussion of current and representative approaches to vehicular communications, and related research challenges, has been accepted for publication in the *IEEE Communications Surveys & Tutorials Journal* [35].

The second contribution is the proposal of an innovative architecture for vehicular delay-tolerant networks (VDTNs) based on the concepts of store-carry-and-forward operation, IP over VDTN, control plane and data plane separation, and out-of-band signaling, which is presented in Section 3.2. A first approach towards the specification of VDTN architecture, was presented at the *3rd IEEE Workshop on Automotive Networking and Applications (Autonet 2008)*, as part of the *IEEE GLOBECOM 2008* [36]. The proposal of the VDTN layered architecture was presented at the *Fourteenth IEEE Symposium on Computers and Communications (ISCC 2009)* [37]. This research work has led to a Portuguese patent request for the VTDTN layered architecture and its corresponding data transmission method. The patent is called "*Método de transmissão de dados em redes veiculares com ligações intermitentes*" (Portuguese) [38] and it was published on October 27, 2010. Also of interest in this context is a paper presented at the *7th Euro-NF Conference on Next Generation Internet (NGI 2011)* [39] that summarizes the main results of the NoE Euro-NF Specific Joint Research Project VDTN - Vehicular Delay-Tolerant Networks.

The third contribution is the proposal and implementation of a simulation tool for vehicular delay-tolerant networks, called VDTNsim, which is described in Section 4.2. The simulation tool was presented at the *15th IEEE International Workshop on Computer-Aided Modeling Analysis and Design of Communication Links and Networks (IEEE CAMAD 2010)* [40].

The fourth contribution is the proposal and implementation of a laboratory testbed for vehicular delay-tolerant networks, called VDTN@Lab, which is presented in Section 4.3. A preliminary version of this prototype was presented at the *5.ª Conferência de Engenharia (Engenharia'2009) - Inovação e Desenvolvimento* [41]. An improved version of the testbed has been used in subsequent studies presented at the *8th Conference on Telecommunications (CONFTELE 2011)* [42], at the *2011 IEEE International Conference on Communications (IEEE ICC 2011)* [43], and at the *16th IEEE International Workshop on Computer Aided Modeling Analysis and Design of Communication Links and Networks (IEEE CAMAD 2011)* [44].

The fifth contribution is a study about the impact of stationary relay nodes on the performance of DTN routing protocols applied to VDTNs, which is presented in Section 5.3. A first performance study, considering only an urban scenario, was presented at the *5th Euro-NGI Conference on Next Generation Internet Networks (NGI 2009)* [45]. An extended version of this paper, studying urban and rural connectivity scenarios with different map areas, node density, and vehicle movement models, has been published as a chapter of the book *Mobile*

Opportunistic Networks: Architectures, Protocols and Applications [46], published by CRC Press – Taylor & Francis Group.

The sixth contribution is an analysis of the influence of movement models and vehicle densities on the performance of DTN routing protocols applied to VDTNs in a rural connectivity scenario, which is presented in Section 5.4. A preliminary version of this study was presented at the *7th Conference on Telecommunications (CONFTELE 2009)* [47]. An extended version of this work was published in the *International Journal of Mobile Network Design and Innovation (IJMNDI), Inderscience Publishers* [48]. This extended version took into account different mobility patterns and node densities, and varied the routing protocols parameters to analyze their effect on the network performance.

The seventh contribution is a study that evaluates how storage constraints on network nodes affect the performance of vehicular delay-tolerant networks. This study, reported in Section 5.5, was presented at the *Second International Conference on Communication Theory, Reliability, and Quality of Service (CTRQ 2009)* [49]. This paper received the "best paper award" at the conference.

The eighth contribution is the influence analysis of node localization information to predict contact duration in order to improve the VDTN network performance, which is presented in Section 3.3 and is evaluated in Section 6.3. This work has been presented at the *2010 IEEE International Conference on Communications (IEEE ICC 2010)* [50].

The ninth contribution is a study of the impact of node cooperation on the performance of vehicular delay-tolerant networks, which is presented in Section 6.4. This study has been accepted for publication as a chapter of the book *Cooperative Networking* [51], published by Wiley.

The tenth contribution is a performance analysis of the impact of scheduling and dropping policies on the performance of VDTN networks, which is presented in Section 6.5. A preliminary version of this study was presented at the *Second International Workshop on Next Generation of Wireless and Mobile Networks (NGWMN-09),* as part of the *38th International Conference on Parallel Processing (ICPP-2009)* [52]. An extended version of this paper has been published in the *International Journal On Advances in Internet Technology, IARIA* [53]. This extended version took into account additional scheduling and dropping policies, which were evaluated in scenarios with different mobile node densities and different mobile node speeds.

The eleventh contribution is a study that considers the problematic of supporting traffic differentiation in a VDTN, which is presented in Section 3.4 and is evaluated in Section 6.6. A preliminary version of this study has been presented at the *17th International Conference on*

Software, Telecommunications and Computer Networks (SoftCOM 2009) [54]. An extended version of this work has been accepted for publication in the *Telecommunication Systems Journal, Springer* [55]. This extended version took into account additional buffer management strategies, and scheduling and dropping policies. Scenarios with different mobile node densities and different mobile node speeds were considered in the performance evaluation.

The twelfth contribution is the proposal, specification, and performance assessment of a new geographic location based routing protocol for VDTNs, named GeoSpray, which is presented in Section 3.5 and is evaluated in Section 6.7. This contribution has been accepted for publication in the *Information Fusion Journal, Elsevier* [56].

1.4. Thesis Organization

This thesis consists of seven Chapters, which are organized as follows. This Chapter, the first, presents the context of the thesis, focusing the topics under studies, the definition of the problem and main objectives, the main contributions, and the document's organization.

Chapter 2 provides the background and related work on vehicular networks and delay-tolerant networks. Chapter 3 first presents a new layered architecture for vehicular networks called vehicular delay-tolerant network (VDTN). Next introduces the concept of node localization, and discusses of the problematic of traffic differentiation in VDTNs. A new routing protocol for VDTN networks, called GeoSpray, is also presented.

Chapter 4 describes the VDTNsim simulation tool and the VDTN@Lab laboratory testbed, which were designed and developed to support research on VDTN networks.

Chapter 5 studies the applicability of VDTNs to provide connectivity to rural and remote regions with limited or non-existing conventional network infrastructures. In this aim, several studies are conducted to evaluate the impact of stationary relay nodes, mobile nodes density and movement patterns, and storage constraints, on the most popular routing protocols for DTN-based networks (Epidemic, Spray and Wait, MaxProp, and PRoPHET).

Chapter 6 presents experiments on improving the performance of VDTN networks. First, the role of node localization as one of the key factors to improve and optimize the use of data plane resources is evaluated. Next, the impact of nodes' cooperative behavior is analyzed in two routing protocols, Epidemic, and Spray and Wait. Then, due to the importance of scheduling and dropping policies in resource-constrained networks like VDTNs, a study to evaluate the performance and tradeoffs of several of these policies is conducted. After that, it focuses on the performance assessment of the proposed mechanisms for supporting traffic differentiation in VDTNs. Later, a performance evaluation of GeoSpray routing protocol is presented. Various performance metrics are used to compare GeoSpray with the following representative routing protocols for DTN-based networks, First Contact, Direct Delivery, Epidemic, Spray and Wait, PRoPHET, and GeOpps. Lastly, an experimental study is presented that uses a testbed to analyze the performance of five common DTN-based routing protocols (Direct Delivery, First Contact, Epidemic, Spray and Wait, and PRoPHET) applied to a vehicular delay-tolerant network.

Finally, Chapter 7 concludes the thesis, summarizing the main research findings and suggesting future research directions.

Chapter 2

Background and Related Work

2.1. Introduction

This Chapter addresses the background and related work for the main topics studied in this thesis, and is organized as follows. Section 2.2 provides an overview on vehicular networks. First, it is presented a selection of the numerous applications envisioned for vehicular networks. An overview of the research projects worldwide that have been conducted to investigate issues related to the development of the infrastructure, applications, and security techniques for these networks is presented. Afterwards, general considerations of routing strategies for vehicular networks are included. The motivation for the use of delay-tolerant networking (DTN) concepts in vehicular networks is discussed at the end of this Section. Section 2.3 provides an introduction to delay-tolerant networks. First, the DTN architecture and its key concepts are reviewed. Next, application scenarios for these networks are presented. Then, some of the most relevant routing protocols for possible use in DTN-based networks are discussed. Afterwards, a literature review regarding topics of interest related with DTN networks and that can be applied to vehicular networks, is conducted, focusing on stationary relay nodes, cooperation, and queuing disciplines. Finally, Section 2.4 summarizes the Chapter.

Part of this Chapter was published in [34, 35].

2.2. Vehicular Networks

As described in the previous Chapter, research in the field of vehicular networks includes a broad range of topics that can be grouped, but are not limited to, the following major areas: wireless access technologies, spectrum issues, power management, data dissemination, routing, quality of service, security and privacy, applications and services, modeling and simulation, and field trials and deployments. Given the focus of this thesis, the related work reviewed in this Section focuses on questions related with data dissemination and routing protocols in vehicular networks. More specifically, it discusses why there is a need to introduce the general concepts of delay tolerant networking (DTN) [21] to sparse or partitioned vehicular networks. The remaining areas (and related topics) presented above, are considered outside the scope of this thesis and thus are not reviewed, although they are interesting research topics for future work. Several review and tutorial papers, and specialized books, reflecting the current developments and state of the art in these areas may be found in [1-3, 5, 9, 14, 60-70].

Before focusing into related work concerning this thesis, it is worthwhile to present some of the applications envisioned for vehicular networks, as well as some of the worldwide research projects and organizations that have been working in this field.

2.2.1. Vehicular Networks Applications

Communication among vehicles, and between vehicles and roadside infrastructure using wireless technology has a large potential for enabling a plethora of applications and services, ranging from time critical applications to delay tolerant applications. These applications can be classified into the following main six categories: road safety, traffic optimization, commercial, entertainment, rural connectivity, and disaster scenario connectivity. The applications presented below, compiled from several sources, represent a sub-set of an ever-growing list.

Vehicular networks are regarded as a key technology in improving road safety. Vehicular communication can assist drivers to prevent an accident from happening, or if an accident occurs to prevent car pile-up. Examples of a diverse range of applications to increase road safety include cooperative collision avoidance [71], collision warning [72, 73], blind spot warning, vision enhancement, emergency break warning, work zone warning, road hazard notification (e.g., icy road, fog), emergency video streaming [74], approaching emergency vehicle warning, speed limit notification, curve speed notification, and cooperative driving.

Vehicular communication can be of great use in enhancing the efficiency of the transportation systems. The goal is to improve the traffic flow and road capacity, through the use of applications and services, such as, traffic condition monitoring [75, 76], platooning (i.e., vehicle following), cooperative notification systems [77], vehicle tracking, lane-changing assistance, freeway management [78], road congestion prevention [76], cooperative driving [79], and toll collection. Vehicular networks can also collect and relay data gathered by a wireless sensor network (WSN) [80, 81] such as weather conditions (e.g., temperature, humidity, rainfall, wind), pollution measurements (e.g., smoke, visibility, noise) [82], road surface conditions, and construction zones [83].

Vehicular networks have other applications beyond road safety and traffic optimization. Examples of some promising commercial applications include dissemination of commercial advertisements [84] (e.g., hotels, restaurants, and gas stations), marketing data, travel (e.g., estimated bus arrival time), tourist and leisure information, and parking space availability [85]. Entertainment applications can provide value-added services to users. For example, the passengers in a vehicle may access the Internet [86] and do cooperative downloads [87, 88], or play games [89], chat [90], and share multimedia content through P2P systems (e.g., music, videos) [91] with passengers in other vehicles.

Vehicular networks are also particularly important in remote regions and rural areas that lack a fixed communication infrastructure. They can enable several non-real time applications, such as file-transfer, electronic mail (e-mail), cached Web access, and health monitoring (telemedicine) [36, 92-96]. Finally, catastrophe hit areas lacking a conventional communication infrastructure, can benefit from the deployment of a vehicular network to provide support for communication between rescue teams and assist communication between the rescue teams and other emergency services [97].

2.2.2. Research Projects on Vehicular Networks

In recent years, there have been several projects worldwide aiming to investigate issues related to both the development of the infrastructure for vehicular communications, applications, and security techniques for these networks. An overview of the principal projects (past, present, and future), organizations and automobile manufacturers that are working in this area is presented below.

The European Project CarTALK 2000 [98] was funded within the IST program in the scope of the 5th Framework Program of the European Commission, which started in 2001 and ended in 2004. This project was focused on driver support assistance systems, which were based upon inter-vehicle communication technologies. Its main objectives were the development of cooperative driver assistance systems for road safety and the development of a self-organising ad-hoc radio network as a communication basis with the aim of preparing a future standard.

The Drive-thru Internet project [99] investigated the usability of IEEE 802.11 [100, 101] wireless local area network (WLAN) technology for providing network connectivity and Internet access to fast moving vehicles. The project envisioned a scenario where hot spots would be available along the road, within a city, on a highway, or even on high-speed freeways. It aimed to develop an architecture for providing connectivity considering difficulties such as intermittent coverage, and to evaluate the communication characteristics using user datagram protocol (UDP) [33] and transmission control protocol (TCP) [102] as transport protocols. This project ended in 2006.

WATCH-OVER [103] project was co-funded by the European Commission Information Society Technologies in the 6th Framework Program of the European Commission, in the strategic objective "eSafety Co-operative Systems for Road Transport". It started in 2006 and ended in 2008. The project’s goal was the design and development of a cooperative system for the prevention of accidents involving vulnerable road users in urban and extra-urban areas.

PReVENT [104] was a European automotive industry activity co-funded by the European Commission. It is another example of a project aimed at contributing to road safety by developing and demonstrating preventive safety applications and technologies.

CARLINK project [105] aimed to develop an intelligent traffic service platform between cars supported with wireless transceivers beside the roads. The platform's primary applications were real-time local weather data, urban transport traffic management, and urban information broadcasting. This project finished in 2008.

The Advanced Cruise-Assist Highway Systems (AHS) [106] was a Japanese intelligent transportation systems (ITS) project conducted by the Advanced Cruise-Assist Highway System Research Association (AHSRA), which started in 1996 and finished in 2008. The project aimed to improve the safety, efficiency, comfort, and convenience of road transportation by incorporating information technology in the road infrastructure.

California Partners for Advanced Transit and Highways (PATH) [107] is a research program administered by the Institute of Transportation Studies at the University of California, at Berkeley, in collaboration with the California Department of Transportation (Caltrans). PATH aims to develop solutions for the problems of California's surface transportation systems. PATH's research is divided into three areas of focus, transportation safety, traffic operations, and modal applications.

The AquaLab project C3 [108] focuses on exploring distributed systems issues in large-scale VANETs. ITS systems rely on infrastructure installed on the roads (e.g., sensors) and networks to provide services like traffic advisory. On the contrary, C3 adopts a cooperative model that depends solely on the information collected by instrumented vehicles through their own sensors and exchanged with other vehicles.

SAFESPOT [109] is an integrated research project co-funded by the European Commission Information Society and Media and supported by European Council for Automotive R&D (EUCAR). This project aims to create dynamic cooperative networks where vehicles and road infrastructure communicate to share information gathered on board and at the roadside, to enable road safety applications.

Adaptive and Cooperative Technologies for the Intelligent Traffic (Aktiv) [110], is a German research initiative with the goal of improving both traffic safety and traffic flow. Aktiv consists of 3 projects related to traffic management, active safety, and cooperative vehicles. This initiative aims to propose novel driver assistance systems, knowledge and information technologies, and solutions for efficient traffic management and car to car (C2C) and car to infrastructure (C2I) communication for future cooperative vehicle applications.

The CAR 2 CAR Communication Consortium [6] is a non-profit industrial driven organization dedicated to road traffic safety and efficiency by means of cooperative intelligent transport systems, with focus on inter-vehicle communications. This consortium was initiated by European vehicle manufacturers (Audi, BMW, Daimler, Fiat, Honda, Opel, Renault, Volkswagen, and Volvo), and supported by equipment suppliers, research organizations, and other partners. It aims to create a European standard for future communicating vehicles spanning all brands.

Network On Wheels (NOW) [7] is a German research project supported by Federal Ministry of Education and Research, which started in 2004. It was founded by Daimler AG, BMW AG, Volkswagen AG, Fraunhofer Institute for Open Communication Systems, NEC Deutschland GmbH, and Siemens AG. The main goals of this project are to solve technical key questions on the communication protocols and data security for C2C communications. The results of this project will be submitted to the standardization activities of the Car2Car Communication Consortium. This project considers the support for active safety applications and infotainment applications.

General Motors Corporation, in conjunction with the Carnegie Mellon University (Pittsburgh, PA USA), has developed research efforts on the proposal of the next generation of vehicle information technology to provide passengers safe and easy access to information and entertainment [8]. The research is divided into the following four areas: dependable embedded systems, design methodologies, human computer Interaction, and wired and wireless multimedia.

The CarTel [111, 112] project is funded by the US National Science Foundation, and in part by the T-Party Project, a joint research program between MIT and Quanta Computer Inc., Taiwan, and in part by Google. This project consists in a distributed, mobile sensor network and telematics system. The system infrastructure includes *i)* software and hardware to collect data from sensors located on mobile units like vehicles and smartphones; *ii)* a content delivery network based on Cabernet [113] and CafNet [114], which uses WiFi from moving vehicles; *iii)* an intermittently connected continuous query database system; *iv)* privacy-preserving protocols for location-based services; and *v)* applications for road surface monitoring and traffic mitigation.

Privacy Enabled Capability In Cooperative Systems and Safety Applications (PRECIOSA) [115] is part of the eSafety initiative, the Information Society and Media initiative, and the Seventh Framework Programme of the European Commission. The project's main goal is to demonstrate that cooperative systems can comply with future privacy regulations. It shows that an intelligent transportation systems application can be set up with technologies for secure and safe communication with assured privacy of the location related data.

Secure Vehicular Communication (SeVeCom) [116] is an EU-funded project that addresses security of vehicle networks, including both the security and privacy of inter-vehicular communication and of the vehicle-infrastructure communication. It focuses on providing a full definition and implementation of a security architecture for these networks.

The EPFL Vehicular Networks Security Project [117] is another example of a project focused on security aspects of vehicular networks. This project focuses on threat model, authentication and key management, privacy, and secure positioning.

The project DRIVE-IN (Distributed Routing and Infotainment through Vehicular Inter-Networking) [118] is developed by researchers from the *Instituto de Telecomunicações*, Faculty of Sciences of the University of Porto, Faculty of Engineering of the University of Porto, University of Aveiro, and Carnegie Mellon University. This project addresses both foundations and applications of inter-vehicle communication. It aims to investigate how vehicle-to-vehicle communication can improve the user experience (i.e., infotainment applications) and the overall efficiency of vehicle and road utilization. The research is divided into three main areas: geo-optimized VANET protocols, intelligent and collaborative car routing, and VANET applications and services.

2.2.3. Vehicular Network Architectures

Vehicular ad hoc networks (VANETs) [1-3, 9, 13-15] were proposed as a special type of mobile ad hoc network (MANET) [119, 120] with the distinguishing property that mobile nodes are vehicles such as cars, trucks, buses, and motorcycles. This implies that mobile nodes movement is restricted to roads, within the constraints of traffic flow and traffic regulations. VANETs are considered an important component of intelligent transportation systems [121-123], which can be defined as systems that use synergistic technologies and engineering concepts in order to improve the safety, security, and efficiency of transportation systems of all kinds.

Vehicle communication in a VANET can be classified as either vehicle-to-vehicle (V2V), vehicle-to-roadside (V2R), or vehicle-to-infrastructure (V2I). Roadside units (RSUs) are static nodes deployed along the road, which are used to improve connectivity and service provision. It is possible for roadside units to be connected to a core network and to the Internet. These concepts are illustrated in Figure 2.1.

Several approaches and architectures have been considered to implement the communication links among vehicles [124]. Examples include a pure V2V ad-hoc network, a wired backbone with wireless last-hop, or a hybrid architecture combining the previous two.

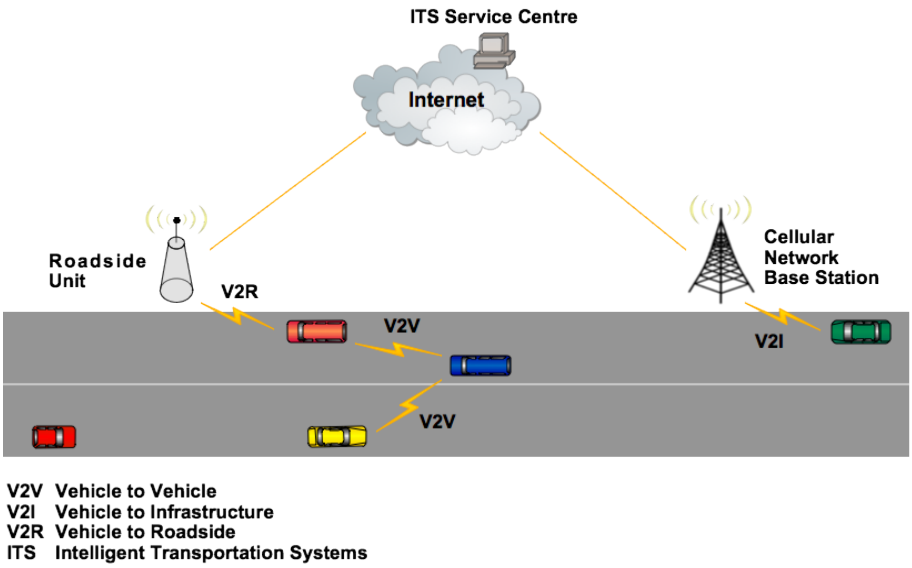

Figure 2.1: Illustration of communication scenarios in a vehicular ad hoc network.

2.2.3.1. Routing in Vehicular Ad Hoc Networks

Traditional routing protocols proposed for MANETs aim at establishing end-to-end paths between network nodes [125-129]. Chennikara-Varghese *et al.* [64], Li and Wang [5], and Lee *et al.* [63] state that these protocols can not be directly applied to VANETs due to their difficulties in dealing with rapid topology changes and frequent fragmentation. Therefore, these routing protocols must be adapted to suit VANETs' unique above-described characteristics, or new protocols must be designed for VANETs. This has been a subject of interest for many researchers over the years, and has resulted in a large number of routing protocol proposals. Detailed theoretical background and surveys of these protocols may be found in [5, 62-65].

It is important to recall that different VANET applications have distinct requirements. A single routing protocol is not capable of efficiently handling all the inherent characteristics of the multiplicity of above-presented applications, as they, for instance, may use unicast, broadcast, or multicast transmission facilities. Hence, attempts have been made to develop routing protocols specifically designed for particular applications. This observation was used by Lin *et al.* [62] to classify recent VANET routing protocols according to a taxonomy that considers three categories: unicast, multicast/geocast, and broadcast. Unicast routing constructs a source-to-destination path. Multicast routing is used to deliver data from one source to many interested recipients. Geocast routing is used to deliver data to a predefined geographic region. Finally, broadcast routing is used to deliver data to all nodes in the network. Figure 2.2 illustrates these routing principles.

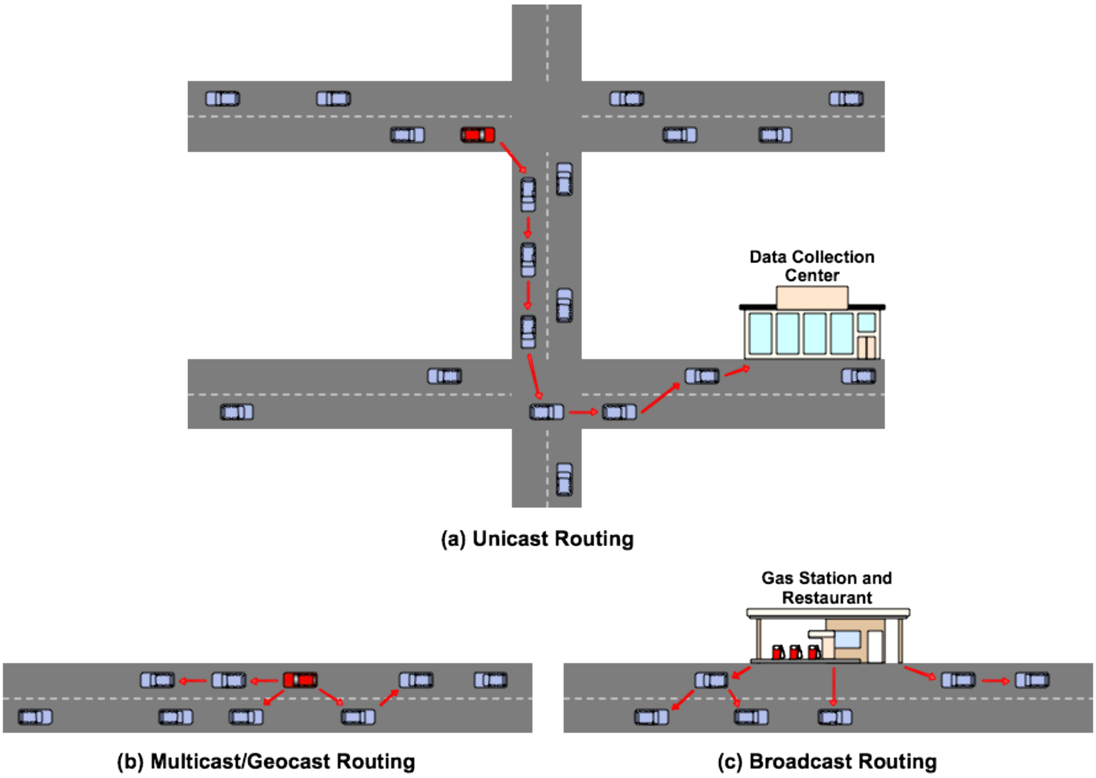

Figure 2.2: Illustration of *(a)* unicast, *(b)* multicast/geocast, and *(c)* broadcast routing schemes.

Both geocast/multicast and broadcast routing is outside the scope of this thesis. Regarding unicast, a taxonomy for these routing protocols was proposed by Lee *et al.* [63], which divides them into two broad categories: topology-based, and position-based. The generic process of these routing strategies is illustrated in Figure 2.3. Topology-based routing protocols use network information about links to perform packet forwarding. This type of routing protocols can be further divided into reactive and proactive protocols. Reactive routing protocols determine routes on a demand or need basis. Proactive routing protocols propagate topology information periodically and find routes continuously between any two nodes in the network, regardless of whether they are needed or not.

Contrary to the previous protocols, position-based routing protocols, also called geographic routing protocols, do not exchange link state information and do not maintain established routes. They make forwarding decisions based on the geographic location of the destination node and the location of neighboring nodes. Hence, it is required that nodes have location capabilities, which can be provided by Global Positioning System (GPS) [130] devices or location services [131-134].

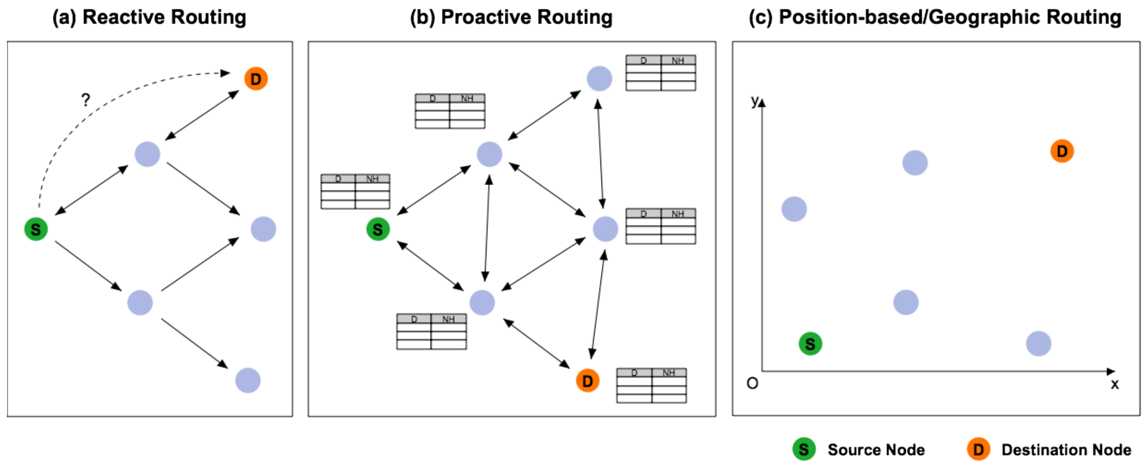

Figure 2.3: Illustration of *(a)* reactive, *(b)* proactive, and *(c)* position-based/geographic routing schemes.

Zhang and Wolff [16, 17] observed that most routing protocol research studies for VANETs consider scenarios like highways and city roads, which are characterized by high node densities. However, urban and rural roads/environments present significantly different conditions, resulting from moderately or low node densities, little or no fixed roadside infrastructure available, and terrain effects. These conditions lead to long periods of time where V2V or V2I communications are infrequent, interrupted, or simply not possible. Wisitpongphan *et al.* [18] also emphasized that the uneven nature of vehicle traffic and market penetration may also be responsible for network fragmentation. Similar observations have also been made by many other authors, including Little and Agarwal [19], Jakubiak and Koucheryavy [2], Abuelela and Olariu [20], and Yousefi *et al.* [3], who have stated that vehicular networks can frequently form partitions and thus prevent end-to-end communication strategies. Hence, the disconnected network problem is an important issue to resolve in emerging vehicular ad hoc network applications.

Since routing protocols designed for fully connected networks are not suitable for data delivery in sparse, intermittent, partially connected vehicular networks, there is a need to design different routing techniques from the perspective that vehicular networks are disconnected by default. To address these issues, researchers incorporated the store-carry-and-forward model of routing proposed for delay tolerant networks (DTNs) [21] into VANETs, as proposed in [10, 11, 22-26]. The idea behind it is to exploit node mobility to physically carry data between disconnected parts of the network. This approach circumvents the lack of an end-to-end path, enabling non real time (i.e., delay-tolerant) applications. These networks are usually referred in the literature to as “DTN enabled VANETs” [11], “Delay Tolerant VANETs” [22], “Delay Tolerant Vehicular Networks” [23], or “Vehicle-Based Disruption-Tolerant Networks” [24]. The concept of delay-tolerant networking is developed more fully in the next Section.

2.3. Delay and Disruption Tolerant Networks

The Internet Protocol suite, commonly known as TCP/IP, makes implicit assumptions of continuous, bi-directional end-to-end paths, short round-trip times (RTT), high transmission reliability, and symmetric data rates [59]. However, a wide range of emerging networks (outside the Internet) usually referred to as opportunistic networks, intermittently connected networks, or episodic networks violate these assumptions. These networks fall into the general category of delay-/disruption-tolerant networks (DTNs) [21]. DTNs experience any combination of the following: sparse connectivity, frequent partitioning, intermittent connectivity, large or variable delays, asymmetric data rates, and low transmission reliability. More importantly, an end-to-end connection cannot be assumed to be available in these networks. Table 2.1 summarizes the main differences between traditional networks (Internet) and DTN networks.

	Traditional (Internet-like)	**DTN**
End-to-end connectivity	Continuous	Frequent disconnections
Propagation delay	Short	Long
Transmission reliability	High	Low
Link data rate	Symmetric	Asymmetric

Table 2.1: Main differences between the assumptions of traditional and delay-tolerant networks.

The TCP/IP stack does not properly handle such connectivity challenges. Firstly, the TCP's performance is severely limited by high latency and moderate to high loss rates. Secondly, the network layer's performance is affected by the loss of fragments. And thirdly, the high latency also causes traditional routing protocols to incorrectly label links as non-operational. This motivated the proposal of a new network architecture that was designed to enable communication under stressed and unreliable conditions.

The work on Interplanetary Internet Architecture, later generalized to DTN architecture, began in the late 1990s [31]. DTN is a field of network research focused on the design, implementation, evaluation, and application of architectures and protocols that intend to enable data communication among heterogeneous networks in extreme environments [21, 29, 135, 136]. In order to answer these challenges the DTN Research Group (DTNRG) [137], which was chartered as part of the Internet Research Task Force (IRTF) [138], proposed an architecture (i.e., RFC 4838) [21] and a communication protocol (i.e., RFC 5050) [29] for DTNs.

The DTN architecture [21], illustrated in Figure 2.4, introduces a store-carry-and-forward paradigm by overlaying a protocol layer, called bundle layer, above the transport layer, which provides internetworking on heterogeneous networks (regions) operating on different transmission media. DTN proposes a new communication paradigm that breaks an end-to-end communication path into hop-by-hop sessions, enabling asynchronous message (i.e., bundle) delivery over physically delayed or disrupted network environments. The bundle protocol [29] is end-to-end, strongly asynchronous, bundle oriented.

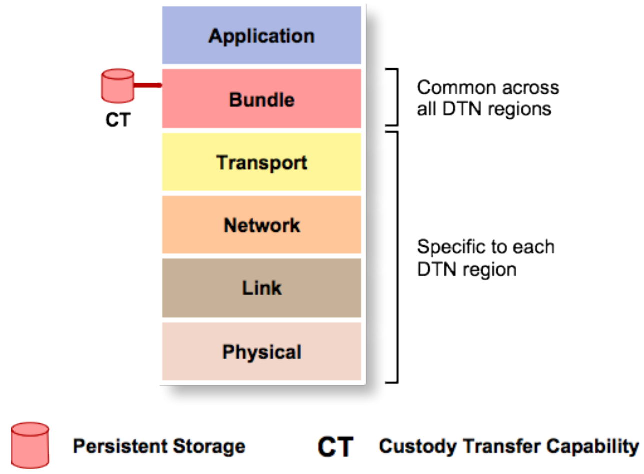

Figure 2.4: Illustration of DTN layered architecture.

In a DTN, the application data units are aggregated into one or more variable-length protocol data units called “bundles”, at the bundle layer. The idea is to “bundle” together all the information required for a transaction (i.e., entire blocks of application-program data and metadata/control information). This minimizes the number of round-trip exchanges, which is useful when the round-trip time is very large. To help routing and scheduling decisions, bundles contain an originating timestamp, a useful life indicator (i.e., time-to-live (TTL)), a class of service assignment for bundle priorities (that can be set to expedited, normal, or bulk in order of decreasing priority), and a length indicator.

The bundle protocol also offers an optional hop-by-hop transfer of reliable delivery responsibility, called bundle custody transfer, and an optional end-to-end acknowledgement functionality (i.e., “return receipt”) [139]. When nodes accept custody of a bundle, they commit to retain a copy of the bundle until such responsibility is transferred to another node. Custody transfer and return receipt functionalities are illustrated in Figure 2.5. Moreover, the bundle layer also implements security services [140, 141] and a flexible naming scheme with late binding [142] that allows bundles destined to a descriptive name to be resolved progressively until they are delivered to one or several recipients.

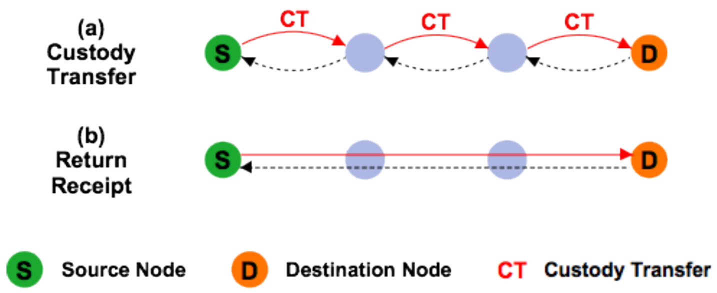

Figure 2.5: Illustration of DTN *(a)* custody transfer and *(b)* return receipt functionalities.

The protocols used in the layers below the bundle layer might be diverse and are chosen according to the communication requirements of each region (e.g., terrestrial Internet, interplanetary networks, or sparse wireless sensor networks). DTN gateways are responsible for forwarding bundles between two or more DTN regions, as illustrated in Figure 2.6. Therefore, they must map data from the lower-layer protocols used in each region they span [136]. This approach allows data to traverse multiple regions, via region gateways, to reach a destination region and, finally, a host within that region.

Protocols below the bundle layer of different regions may provide different semantics, thus protocol-specific convergence layer adapters are required to provide the functions necessary to carry the bundles on each of the corresponding protocols. An example of a work in progress as an internet-draft for a TCP-based convergence layer protocol can be found in [143]. Another example is provided in [144], where a vehicle transmission protocol (VTP) and its correspondent convergence layer for DTN is discussed.

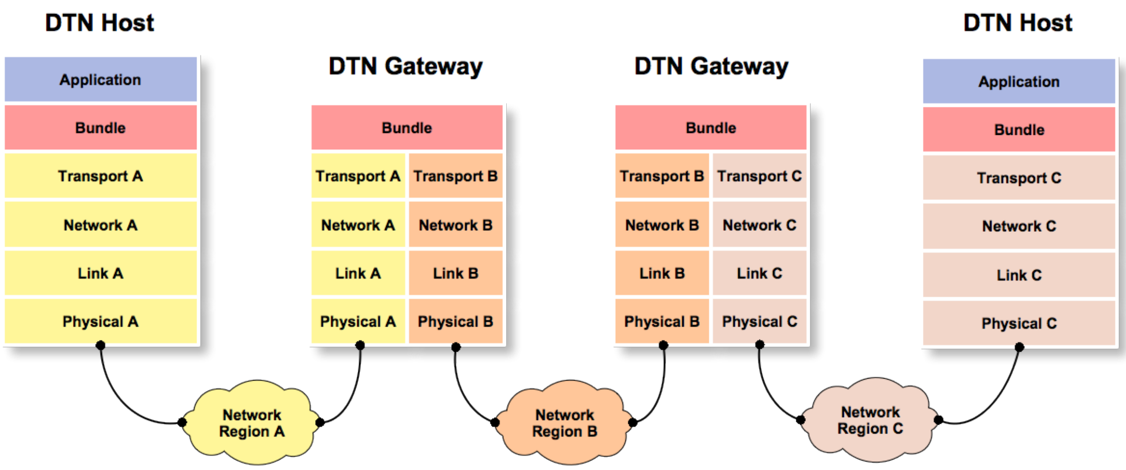

Figure 2.6: DTN bundle protocol architecture, and DTN host and gateway concepts.

The store-carry-and-forward paradigm avoids the need for constant connectivity. It is used to move bundles across a region, exploiting node mobility. This paradigm, which is illustrated in Figure 2.7, can be described as follows. A source node that originates a bundle, stores it using some form of persistent storage (such as a hard disk) and physically carries it while waiting until a communication opportunity becomes available. When a contact opportunity occurs (i.e., two nodes are in range), the bundle is forwarded to an intermediate node, according to a hop-by-hop forwarding/routing scheme. Then, this process is repeated and the bundle will be relayed hop-by-hop until eventually reaching its destination node.

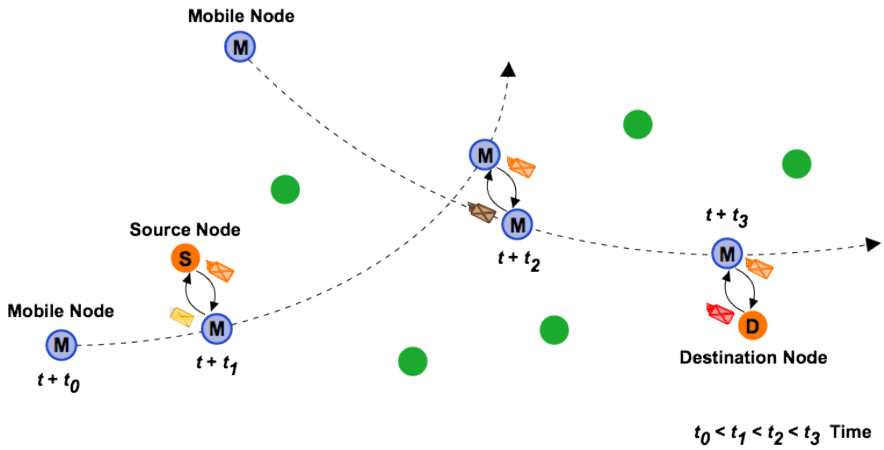

Figure 2.7: Illustration of the DTN store-carry-and-forward paradigm.

A contact is defined as a time period during which two network nodes have the opportunity to communicate and it depends on the application area [145]. DTN architecture [21] defines different types of contacts that can be classified as persistent, on-demand, scheduled, predicted, or opportunistic. In persistent contacts, links are always available and no action is required to instantiate such a contact. On-demand contacts are similar to persistent contacts, but require some action in order to instantiate. In scheduled contacts, it is assumed that nodes move along predictable paths. Therefore it is possible to predict or receive time schedules of their future positions. Thus, communication sessions will be scheduled, i.e., the contact is established at a particular time, for a particular duration. Predicted contacts require analyzing previous observed contacts (or some other information) to predict the future opportunities (i.e., the contact times and durations) to transmit data. In opportunistic contacts, communication opportunities happen unexpectedly, without any prior knowledge.

There may be some situations where contacts between network nodes are of such a short duration that a bundle can be inevitably too large to be sent in one piece. This results in incomplete bundle transmissions. DTN architecture considers the use of fragmentation and reassembly to ensure that contact volumes are fully utilized, thus avoiding the retransmission of partially transmitted bundles. Two types of fragmentation/reassembly are proposed: proactive and reactive [21]. In proactive fragmentation, a node splits a bundle into smaller fragments prior to a transmission attempt and then transmits each fragment as an independent bundle over the DTN network. The fragmentation decision may be based on knowledge of the link availability (ahead of time) or account for buffer limitations on the next node, among others.

In reactive fragmentation, the fragmentation process is executed after an attempted transmission has occurred. In this case, a node may learn via lower-layer convergence protocols that only a portion of the entire bundle was transmitted to the next node, for instance due to a sudden link failure. Then, both nodes can cooperatively reconcile the remaining and the already received portions into valid (fragmented) bundles, which can be sent at new contact opportunities.

For both fragmentation types, the fragments are only reassembled into the original larger bundle at the destination node. Fragments may be further fragmented, either proactively or reactively. A study on the effects of fragmentation on the bundle delivery success in DTNs is presented in [146].

2.3.1. Application Scenarios

The DTN concept was initially designed for communicating with spacecrafts, to compensate for disconnections over interplanetary distances [31, 147]. Interplanetary networking (IPN) is characterized by high intermittent connectivity, extremely long propagation delay (due to the finite speed of light), low transmission reliability (due to the positioning inaccuracy and limited visibility), and low and asymmetric data rate. Several projects have been carried out on this topic by several organizations, such as InterPlaNetary Internet Project [148], Defense Advanced Research Projects Agency (DARPA) [149], NASA Jet Propulsion Laboratory [150], and MITRE - Applying Systems Engineering and Advanced Technology to Critical National Problems [151].

However, over the years, researchers have identified numerous terrestrial environments where DTN concepts may be employed. For example, underwater networks make use of DTN paradigm to cope with the problems caused by intermittent connectivity, mobility, sparse deployment, high propagation delay, high transmission cost, low asymmetric data rate, and poor transmission reliability (due to positioning inaccuracy and high attenuation). These networks enable applications for oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, assisted navigation, and tactical surveillance applications [152, 153]. Examples of projects in this area include Underwater Acoustic Sensor Networks (UW-ASN) [154], UAN - Underwater Acoustic Network [155], and SiPLABoratory [156].

Wildlife tracking networks, which are designed for biology research, may consider a DTN approach to face the problems resulting from intermittent connectivity, mobility, sparsity, energy constraints, large end-to-end delay, and asymmetric data rate. These networks allow monitoring the long-term behaviours of wild animals sparsely distributed over a large area. Examples of projects for animal tracking are ZebraNet [157, 158], SWIM [159], and TurtleNet [160].

Sparse wireless sensor networks (e.g., space, terrestrial, and airborne) can also apply DTN technology to deal with the problems caused by intermittent connectivity, sparse deployment, limited power (and also limited memory and CPU capability), and low and asymmetric data rate [161-163]. These networks are usually employed to monitor science and hazard events, like earhquakes, volcanos, flooding, forest fire, sea ice formation and breakup, lake freezing and thawing, and environmental monitoring. Some examples of projects in this area are Volcano Sensorweb [164] and Sensor Networking with Delay Tolerance (SeNDT) [165].

The problem of providing data communications to remote and underdeveloped rural communities in developing countries has been addressed by several projects with approaches that focus on asynchronous (disconnected) messaging by transportation systems. Vehicles are used as data mules, carrying data to remote villages and regions where there is no network infrastructure. Such approach reduces the cost of connectivity and allows dealing with intermittent connectivity, mobility, sparse deployment, high propagation delay, and asymmetric data rate issues [96, 166]. Examples of projects in this area are the following: DakNet [94], Saami Network Connectivity (SNC) [95], Wizzy Digital Courier [93], Message Ferry [167, 168], Networking for Communications Challenged Communities (N4C) [92], First Mile Solutions [169], KioskNet [170, 171], and Affordable Internet Access Project for Underdeveloped Communities [172].

People networks, also called pocket switched networks and social networks, explore transfer opportunities between mobile wireless devices carried by humans [173-178]. These networks experience the problems imposed by intermittent connectivity, mobility, energy limitation, heterogeneous, and asymmetric data rate. They enable applications that forward data based on people's social interest (e.g., news, music, movies, and arts). The Haggle project [179] is an example in this area.

Integrating DTN concepts to military tactical networks can ease communications in hostile environments (battlefields) where a network infrastructure is unavailable [149, 180-182]. These networks suffer from problems of high intermittent connectivity, mobility, destruction, noise, attack, interference, low transmission reliability (due to position inaccuracy and limited visibility), and low data rate. The Marine Corps Command and Control, On-the-Move, Network, Digital, Over-the-horizon Relay (CONDOR) [183] program is an example in this area.

DTN principles can also be considered for disaster recovery networks. These networks can support communications between emergency responders in catastrophe-hit areas lacking a functioning communication infrastructure [97, 184-186].

2.3.2. Routing Protocols

Routing in DTNs is a challenging issue because of the lack of contemporaneous end-to-end paths. Furthermore, information and resource shortage accentuate this challenge. It is important to note the importance of node mobility, which is exploited to carry data around the network and thus to overcome network partitions.

In these networks, routing consists in a sequence of independent, local forwarding decisions that make bundles "progress in steps" towards their destination. The source of knowledge that is used to take these decisions often differs, and can be used to classify routing protocols. While some routing approaches assume that there is not any knowledge available, others consider and eventually combine information about historical data (e.g., recent encounters, contact time, contact frequency, or contact location), location (e.g., past, present, future location data), or movement patterns.

DTN routing strategies can also be classified as single-copy schemes (i.e., forwarding-based) or multiple-copy schemes (i.e., flooding-based) [187-189]. Single-copy schemes maintain a single copy of a bundle in the network that is forwarded between network nodes. These routing schemes have low resource requirements (e.g., storage, bandwidth, energy), however, they suffer from low delivery ratios and large delays. On the contrary, multiple-copy schemes replicate bundles at contact opportunities. Copies of the same bundle can be routed independently to increase security [190] and robustness (i.e., the chances of delivery via different paths). Bundle replication improves the probability of delivery and minimizes the delivery latency. The downside is that it consumes a high amount of energy, and increases the contention for network resources like bandwidth and storage. Therefore, it potentially can lead to poor overall network performance, as discussed in [189, 191]. These shortcomings often make multiple-copy routing strategies improper for energy-constrained and bandwidth-constrained DTN applications.

The next Subsubsections present examples of single-copy and multiple-copy routing protocols, which are aimed at generic application scenarios. Therefore, they can be potentially used in any DTN-based network, such as a sparse vehicular network. Detailed theoretical background and surveys of DTN routing protocols may be found in [145, 187, 188, 192-195].

2.3.2.1. Single-copy Routing Protocols

Direct Delivery/transmission [196] and First Contact [194] are two examples of simple single-copy DTN routing protocols. These protocols do not use any knowledge about the network to make forwarding decisions. In Direct Delivery [196], the source node carries the bundle until it meets the destination node. Thus, although this protocol has minimal overhead, it may incur in very long delays for bundle delivery. Its operation is illustrated in Figure 2.8.

First Contact [194] performs routing by forwarding bundles randomly, as illustrated in Figure 2.9. Nodes forward bundles to the first node they encounter. This results in a random search for the destination node. Moreover, bundles may oscillate among a set of nodes or be delivered to a dead end.

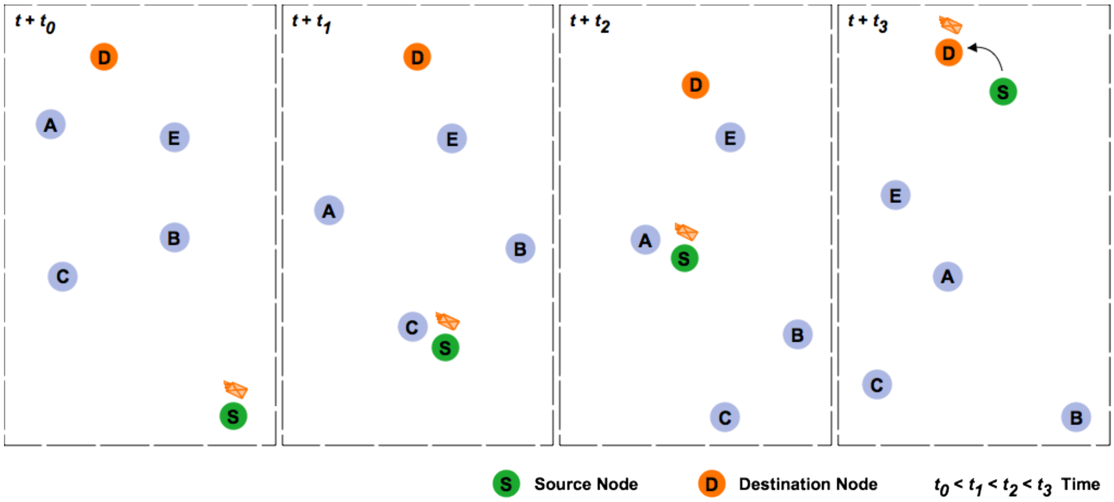

Figure 2.8: Illustration of the Direct Delivery routing protocol operation.

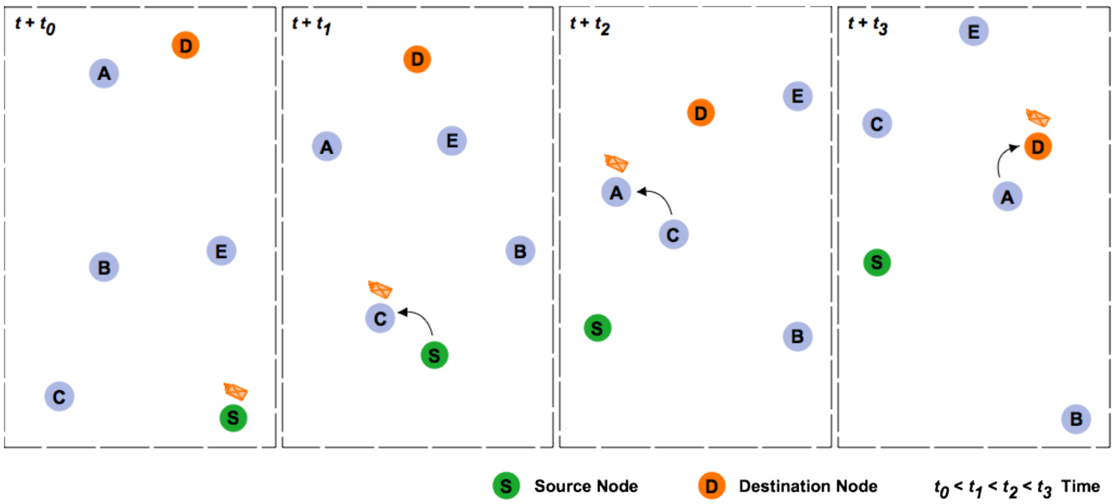

Figure 2.9: Illustration of the First Contact routing protocol operation.

These basic routing approaches can be enhanced considering a utility function that evaluates the capability of the encountering nodes to deliver a bundle to its destination. One possibility would be to incorporate location information to assist in making the forwarding decisions. Such an algorithm belongs to a class of routing protocols known as geographic routing protocols (also known as location-based or position-based routing protocols).

Geographic routing relies mainly on location information and other mobility parameters provided by positioning devices such as global positioning systems (GPS) [130]. In this class of routing protocols, routing decisions are made with the goal of, at each step, progressively reducing the geographic distance to the destination node(s). Hence, it is assumed that nodes know their geographical location and the geographical location of the destination node(s).

The increasing availability of vehicle navigation systems (NS) has sparkled the development of geographic routing approaches to vehicular networks. A NS features location hardware (typically a GPS), a roadmap database containing several information, such as, speed limit and average speed, and a shortest path algorithm. With this plethora of information it is possible to estimate the arrival time to a specific location (namely of a given destination node).

Although several geographic routing protocols have been proposed for vehicular communications, most approaches do not apply to sparse (low node density) scenarios. Examples include the position-based routing strategies for VANETs presented in [197-199], which are not able to deal with intermittency, disruption, or frequent network partitions that can last for a long period of time. On the contrary, Geographical Opportunistic Routing (GeOpps) [25] is an example of a routing protocol that follows the store-carry-and-forward paradigm to cope with these issues.

GeOpps is a forwarding routing protocol that maintains a single copy of each bundle in the network, and its routing decisions are made as follows. A vehicle moving along a suggested route (determined in function of its destination) uses its navigation system to determine the nearest point (*NP*) on its route to a location (*D*) where a data bundle must be delivered. Figure 2.10 shows an example of *NP* calculation for three vehicles *A*, *B*, and *C*. Then, the navigation system is used to estimate the time of arrival (ETA) of the vehicle to the *NP*, and to determine the ETA needed to go from *NP* to *D*. The sum of these values is called the minimum estimated time of delivery (METD) as shown in Equation 2.1, and it is used as an utility function to make routing decisions.

$$METD = ETA \ \ to \ \ NP + ETA \ \ from \ \ NP \ \ to \ \ D \tag{2.1}$$

During a vehicle travel, a bundle is forwarded to an encountered vehicle, only if the METD required by the encountered vehicle to deliver the bundle is lower than the METD of the vehicle that currently carries the bundle. This would mean that the encountered vehicle is likely to move closer and/or faster to the bundle's destination. This process is repeated until the bundle reaches its destination or its time-to-live expires.

Figure 2.10 shows an example where a vehicle *A*, which is carrying a bundle to be delivered to *D*, meets a vehicle *B* at location P_1. The *NP* calculation for *A* and *B*, allows concluding that *B*'s METD value is lower than *A*'s METD. This happens because the time required to go from P_1

to NP_B and then to *D* is lower than time required to go from P_1 to NP_A and then to *D*. Hence, *A* forwards the bundle to *B*. Afterwards, during its travel, the vehicle *B* encounters vehicle *C* at location P_2. Since *C* is going to pass closer to the destination of the bundle, it has a lower METD than *B*. Thus, vehicle *B* forwards the bundle to *C*.

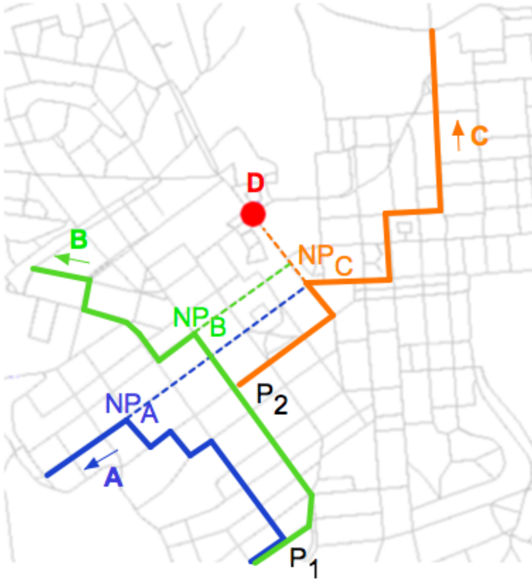

Figure 2.10: Example of GeOpps calculation of the nearest point (*NP*) from bundle's destination (*D*), for vehicles *A*, *B*, and *C*.

2.3.2.2. Multiple-copy Routing Protocols

Some examples of well-known and widely investigated multiple-copy DTN routing protocols are Epidemic [200, 201], Spray and Wait [202], PRoPHET [203, 204], and MaxProp [24]. These protocols are aimed at generic application scenarios. Therefore, they can be potentially used in any DTN-based network, such as a vehicular network that delivers data using a store-carry-and-forward paradigm. These routing protocols make different assumptions about the knowledge available to network nodes (e.g., absence of knowledge or history of node encounters), as discussed below.

Epidemic protocol [200, 201] does not require any prior knowledge about the network. Under this routing protocol, each node maintains a list of the bundles it carries that have not been delivered. At node encounters, network nodes exchange all bundles that they don't have in common. Using this strategy, all bundles are eventually spread to all nodes, including their destination. Figure 2.11 clarifies the protocol operation.

Epidemic is shown to be effective, but suffers from the disadvantages of flooding as the node density increases. It creates lots of contention for buffer space and required bandwidth, resulting in many bundle drops and retransmissions in resource-constrained network environments. In an environment with infinite buffer resources and bandwidth, this protocol provides an optimal solution, since it delivers all the bundles that can possibly be delivered in the minimum amount of time. For this reason, it is considered “unbeatable” and it is used as a benchmark to compare with other routing protocols [193].

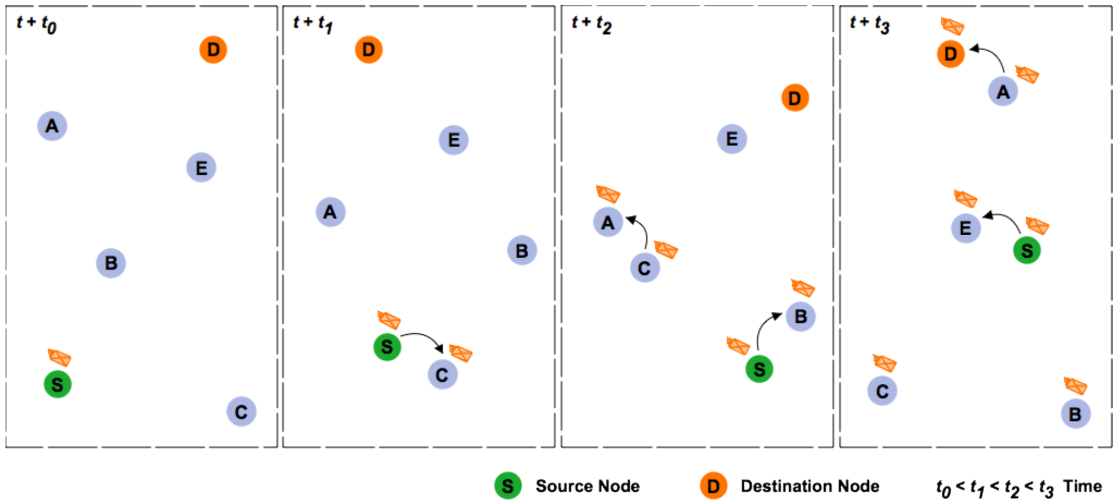

Figure 2.11: Illustration of the Epidemic routing protocol operation.

Spray and Wait [202] limits the number of bundle replicas (i.e., copies) per bundle allowed in the network to control flooding. This routing protocol assumes two main phases. In the “spray phase”, for each bundle originated at a source node, L bundle copies are spread to L distinct nodes. If the destination node is not found during the “spray phase”, then at the “wait phase” direct transmission is performed. Hence, it waits until one of the L relays (i.e., nodes) finds the destination node.

Two different spraying schemes are proposed for the “spray phase”, *source spray* (also called *normal spray*) and *binary spray*. In the *source spray* scheme, the source node starts with L bundle copies. Each time the source node encounters a new node, it hands one of the L copies, and reduces its number of copies left by one. In the *binary spray* scheme, the source node also starts with L bundle copies. But, whenever a node with $L > 1$ copies encounters a new node, it hands half of the copies that it stores in its buffer.

For both spraying schemes, when a node carries only 1 bundle copy left, it only forwards it to the final destination. This is the “wait phase”. Figure 2.12 and Figure 2.13 illustrate, respectively, Source Spray and Wait, and Binary Spray and Wait routing protocol operation. It is important to notice that each bundle has a header field indicating the “number of copies” it represents. As expected, the (actual) bundle is not replicated within a node’s buffer.

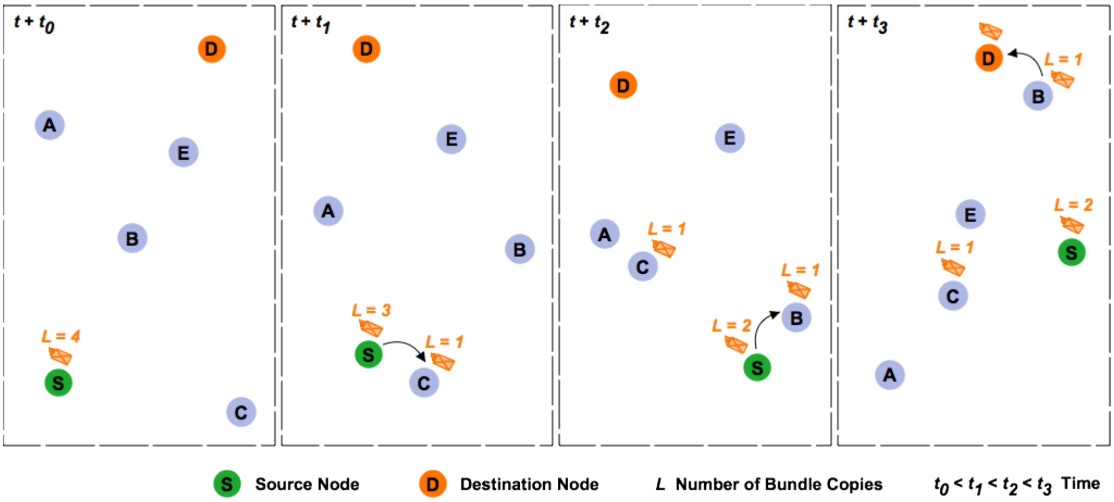

Figure 2.12: Illustration of the Source Spray and Wait routing protocol operation.

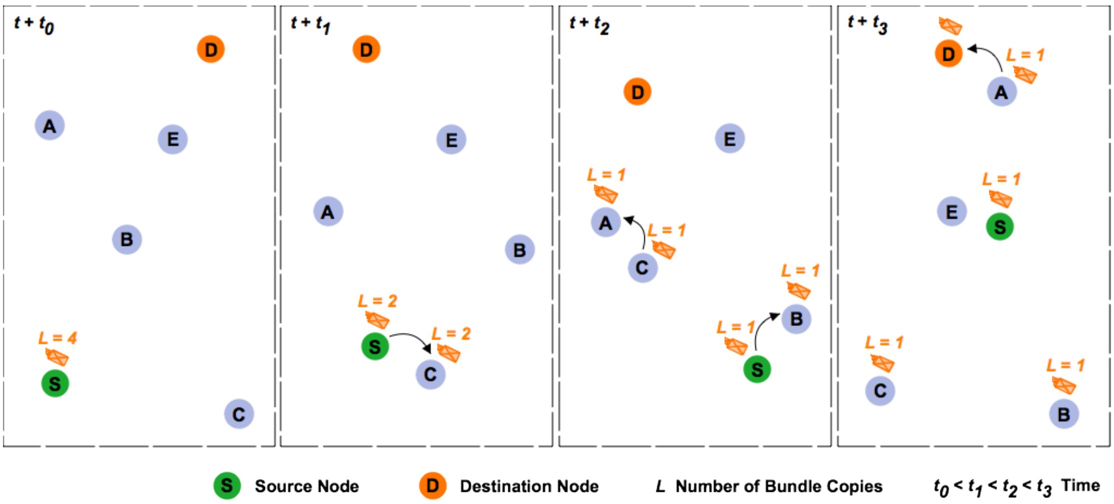

Figure 2.13: Illustration of the Binary Spray and Wait routing protocol operation.

PRoPHET [203, 204] considers that network nodes move in a non-random pattern and applies "probabilistic routing". This protocol uses the concepts of history of node encounters and the transitivity property illustrated in Figure 2.14, which can be defined as follows. The history of node encounters defines $P_{(a,b)}$ as the probability that two nodes, a and b, meet each other. It is calculated as shown in Equation 2.2, where P_{init} is an initialization constant.

$$P_{(a,b)} = P_{(a,b)_{old}} + (1 - P_{(a,b)_{old}}) \times P_{init} \quad , \quad P_{init} \in [0,1] \tag{2.2}$$

This probability, called delivery predictability, is renewed with each successive contact between the same nodes. It may also decay over time if these nodes don't meet. Thus, between two meetings the predictability value ages. The aging equation is shown in Equation 2.3, where γ is the aging constant and k is the elapsed time since last ageing.

$$P_{(a,b)} = P_{(a,b)_{old}} \times \gamma^{k} \quad , \quad \gamma \in [0,1) \tag{2.3}$$

The transitivity property $P_{(a,c)}$ of the delivery predictability is based on the observation that if node A frequently encounters node B, and node B frequently encounters node C, then node B probably would be a good node to forward bundles that are destined to node C, and vice versa. Transitivity is calculated as shown in Equation 2.4, where β is scaling constant that decides the impact of the transitivity on the delivery predictability.

$$P_{(a,c)} = P_{(a,c)_{old}} + (1 - P_{(a,c)_{old}}) \times P_{(a,b)} \times P_{(b,c)} \times \beta \quad , \quad \beta \in [0,1] \tag{2.4}$$

The delivery predictability metric is calculated in all network nodes for each known destination. It is updated each time a node is encountered and it is used to decide whether or not to forward bundles at communication opportunities. Thus, when a contact opportunity occurs, the involved nodes exchange the delivery predictability information stored on them. Both nodes use this information to update their own estimated delivery predictability information. Then, based on this information and on the bundles destination, a bundle is forwarded to the other node if the delivery predictability of the destination of that bundle is higher at the other node.

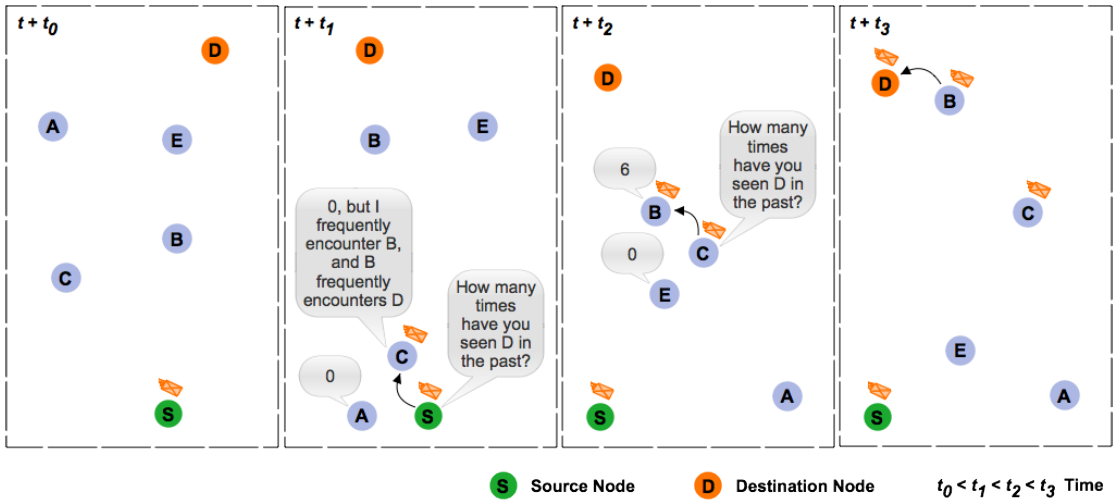

Figure 2.14: Example of using the historic of node encounters and transitivity information, as basis for PRoPHET routing decisions.

MaxProp [24] is a generic routing protocol for vehicular DTNs. It performs routing by prioritizing the scheduling of bundles forwarded at contact opportunities, and also the scheduling of bundles to be dropped upon buffer overflow. To calculate these priorities the protocol considers the historical data of path probabilities to nodes, which is determined as follows. Each node i holds a vector f^i that represents its likelihood to meet every other node available in the network. The likelihood of node i meeting node j is initially set according to Equation 2.5, where n represents the total number of nodes that exist in the network. Each time i meets j the f^i_j entry of the vector is increased by 1. Then, the vector of likelihood is re-normalized using incremental averaging according to Equation 2.6. As a result, nodes that are seen infrequently score lower values over time.

The access to the information contained in the vector of likelihood from the other nodes allows determining which bundles should be sent and deleted from the buffer, based on path calculation using subsequent likelihoods.

$$f_j^i = \frac{1}{n-1} \tag{2.5}$$

$$\sum_{j=1}^{n-1} f_j^i = 1 \tag{2.6}$$

This protocol also includes three principal complementary mechanisms, namely: head start for new bundles, lists of previous intermediaries, and system-wide acknowledgments. In order to guarantee that all bundles have a chance of being propagated in the network, a “head start” is given to new bundles. This means that priority is given to the transmission of these bundles. Lists of previous intermediaries are maintained to prevent bundles of being sent to the same node again. System-wide acknowledgments are propagated through the network in order to notify nodes to eliminate redundant copies of the bundles that have already been delivered to their destination.

MaxProp has been implemented on a real bus-based DTN network called UMass DieselNet [205]. This protocol has been shown to perform well in a wide variety of DTN environments.

2.3.3. Stationary Relay Nodes

The frequency and the number of contact opportunities plays an important role in the performance of a DTN. In fact, in extremely sparse scenarios with low node density, direct contacts between nodes can be so infrequent that even the store-carry-and-forward paradigm is insufficient, by itself, to accomplish data delivery. It is interesting to note that, in scenarios like a sparse vehicular network, mobile nodes (i.e., vehicles) may not come to direct contact with each other, however they may pass at the same location, in different times, one after the other. This motivates the introduction of stationary relay nodes, as extra-infrastructure elements that can be strategically placed to increase contact opportunities between mobile nodes.

In vehicular networks, stationary relay nodes can be defined as fixed nodes with store-and-forward capabilities that are installed at road intersections, allowing passing-by vehicles to collect and leave data bundles on them. Figure 2.15 illustrates an example where a stationary relay node is deployed on a crossroad, creating an additional contact opportunity that would not exist before, since vehicles would not meet each other. When passing along the crossroad, vehicle *A* exchanges bundles with the stationary relay node at time $t+t_0$. Following a different route, vehicle *B* passes along the stationary relay node at a later time $t+t_1$, collecting bundles left there by vehicle *A*.

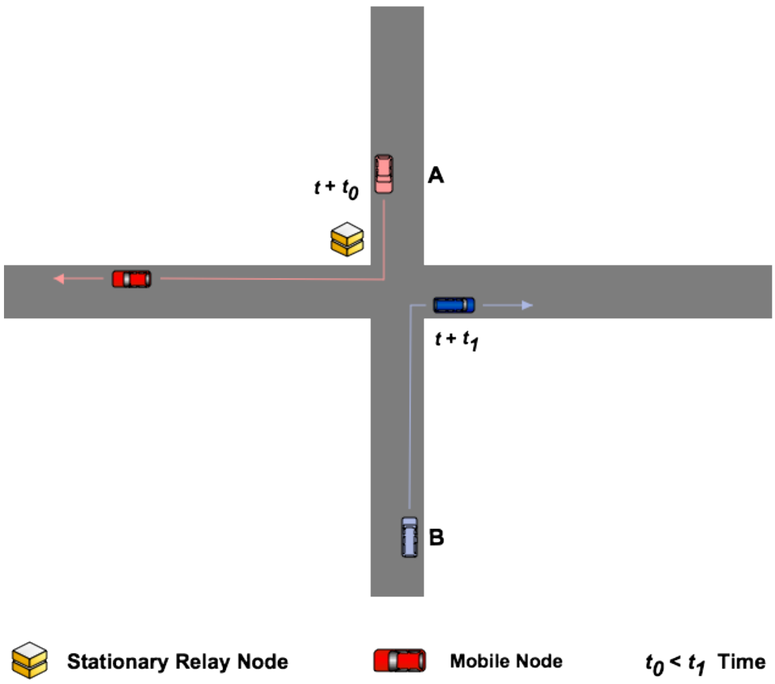

Figure 2.15: Illustration of the data exchange among vehicles and a stationary relay node deployed at a road intersection.

Despite the importance of stationary relay nodes, there is few related work on the problem of increasing the performance of a vehicular-based DTN with the deployment of these nodes. Zhao *et al.* [206] have used the term “throwbox” to refer to a stationary relay node. They presented a study focusing on improving bundle delivery in DTNs using throwboxes. The work presented a framework to investigate the issues related with throwbox deployment and routing. This framework considered distinct deployment scenarios differing on the information available about contact opportunities or traffic matrix. For each of these scenarios, different routing protocols were considered. The authors showed that to maximize the throwboxes' effectiveness, their placement should be considered simultaneously with the routing algorithm.

Following the previous work, Banerjee *et al.* [207] concluded that due to possible energy constraints, deploying throwboxes without using efficient power management schemes is minimally effective on the sparse connectivity of DTN scenarios. Therefore, they proposed an energy efficient hardware and software architecture for throwboxes, separating neighbor discovery from data transfer. Low-power, long-range, low-bit-rate radio hardware is used for neighbor discovery. Based on the information collected about neighbor discovery and mobility prediction, the high power, short-range, and high-bandwidth radio hardware is turned on if necessary, and only during the time that lasts the contact opportunity. This architecture attempts to meet energy constraints, while maximizing the packet delivery ratio.

Banerjee *et al.* [208] also studied the tradeoffs of mobile networks enhanced with the deployment of relays, meshes, and wired base stations infrastructure. A cost-benefit analysis was provided, and the authors identified scenarios where wireless mesh or disconnected relays are a better choice than base stations/info stations, due to their ease and cost of deployment. They also observed that a greater number of relays and mesh nodes are needed to achieve a similar performance of base stations.

A network architecture based on the concept of DTN, called vehicular wireless burst switching (VWBS), was proposed Farahmand *et al.* in [36]. VWBS considers the use of relay nodes to provide better connectivity on sparse rural regions and discusses their importance to improve the network performance in terms of the average packet delay and the packet loss. Their work proposed several heuristic algorithms to provide a solution to the "relay node placement problem". This problem was formulated as follows: given a previously known network topology, vehicles mobility model, traffic matrix, and the number of available relay nodes, the goal was to determine in which road intersections should be placed relay nodes, in order to maximize the network performance in terms of network cost (minimizing the number of relay nodes), delay (minimizing delivery time), or both (minimizing the number of relay nodes and delivery time).

The previous work was extended in [209], where the authors showed that the problem of optimal relay node placement is an NP-hard problem, and proposed an integer linear programming (ILP) formulation to this problem. Two heuristic algorithms were also presented. One of the algorithms aimed at minimizing the number of hop counts between source and destination terminal nodes, while the other aimed at minimizing the average message delivery time to the destination. Moreover, both algorithms also attempt to minimize the number of required relay nodes in the network.

Ibrahim *et al.* [210] also presented a work related to this topic, considering the use of markovian models to study the impact of adding throwboxes on the delivery delay and resource consumption of mobile ad hoc networks [119]. The study considered cases where throwboxes are fully disconnected or mesh connected, quantifying the impact of the number of throwboxes over the performance of routing protocols for each case.

2.3.4. Cooperation

The effective operation of DTN-based networks relies on the cooperation among network nodes to store-carry-and-forward data over partitioned and challenged network environments. Nodes must share their limited storage, bandwidth, and energy resources to mutually enhance the overall network performance. Until recently, most of the research on these networks has assumed that nodes are fully cooperative. In a cooperative environment, network nodes collaborate with each other, storing and distributing bundles not only in their own interest, but also in the interest of other nodes. Such a behavior increases the number of possible transmission paths, improving the robustness to failure of individual nodes. However, this assumption may not be realistic, since network nodes may exhibit a selfish behavior. Figure 2.16 illustrates a non-cooperative environment, where a network node denies storing and distributing the other nodes' bundles and, at the same time, exploits the other nodes resources to disseminate its data. This behavior can be caused by several reasons, such as resource limitations (e.g., storage, energy) or rogue operation (i.e., malicious behavior). More importantly, it leads to overall degradation of the network performance.

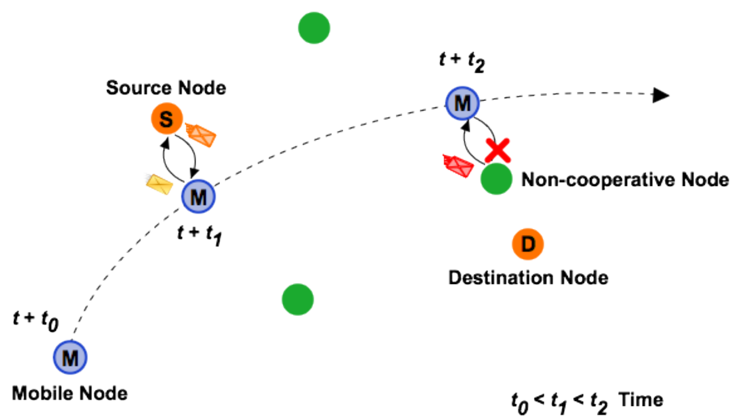

Figure 2.16: Illustration of a non-cooperative network scenario.

Although cooperation is crucial for improving the limited capability of network nodes and, consequently, for increasing the overall network performance, to the best of our knowledge, little research has been done in this field. Panagakis *et al.* [211] stated that the literature related to the performance of DTN routing protocols usually assumes fully cooperative environments, which can be an unrealistic assumption, since network nodes may be unable to cooperate due to resource constraints, to a selfish behavior, or to a common strategy. The authors have not proposed any mechanisms to detect non-cooperative behavior or to enforce cooperation among network nodes. They defined cooperation as the probability of a node to forward message copies or dropping them on their arrival, and evaluated its effect in terms of delivery delay and transmission overhead on Epidemic, Two-Hop [212], and Binary Spray and Wait DTN routing algorithms. The results presented in this study revealed the importance of considering cooperation effects on the network performance. Algorithms that perform better under a fully cooperative environment can be outperformed in non-cooperative environments. It was also observed that, in general, Two-Hop routing algorithm is more resilient to less cooperative node behavior.

Buttyán *et al.* [213] studied the problem of selfish node behavior in DTNs used for personal wireless communications. In this work, a mechanism to discourage selfish node behavior during message exchange based on the principles of barter was proposed. This barter-based approach was analyzed with a game-theoretic model. Simulation results showed that this approach indeed stimulates cooperation among network nodes.

Shevade *et al.* [214] also demonstrated the degradation of a DTN network performance due to selfish node behavior. In their opinion, this motivates the need to introduce an incentive mechanism to stimulate cooperation. In this sense, an incentive-aware DTN routing scheme is proposed based on the use of pair-wise tit-for-tat (TFT) incentive mechanism. TFT is based on the principle that every node forwards as much traffic for a neighbor as the neighbor forwards for it. This routing strategy allows selfish users to optimize their performance without significantly deteriorating the system-wide performance. A simulation-based study showed that the proposed routing protocol effectively stimulates cooperation among selfish network nodes and thus improves the overall delivery ratio.

Morillo-Pozo *et al.* [23, 215] proposed a variation of the cooperative ARQ (C-ARQ) scheme to be used in delay-tolerant vehicular networks. The main objective of this scheme was to reduce packet losses in transmissions between fixed access points located along the roads and passing-by vehicles. Vehicles buffer all data sent by access points. Cooperation between vehicles is established in areas where there is no connectivity to the access points. In these areas, vehicles request packets incorrectly received or lost (from the access point) to near-by vehicles. This scheme intends to allow network nodes to work cooperatively in order to increase their delivery rate. The performance of the proposed scheme was evaluated through an experimental prototype running in a real urban environment. The obtained results have shown that using this cooperation scheme packet loss can be halved for transmissions between vehicles and access points. This study was extended in [216] by the same authors, where a new cooperative ARQ protocol scheme named DC-ARQ (Delayed Cooperative ARQ) was proposed. Contrary to C-ARQ cooperation that occurs in a packet-by-packet basis, in DC-ARQ the cooperation is delayed until vehicles are out of the range of the access point.

Following the above-mentioned works [23, 215, 216], Trullols-Cruces *et al.* [217] presented a vehicular framework that benefits from two cooperative mechanisms. A DC-ARQ scheme is used to reduce packet losses in the transmissions between network nodes (vehicles and access points). In addition, vehicle route prediction together with a carry-and-forward paradigm is used to improve throughput, delay and the number of access points. Through simulation, the authors showed that sparse vehicle scenarios benefit more from the carry-and-forward paradigm, while dense vehicle scenarios benefit from the DC-ARQ scheme.

Resta *et al.* [218] presented a theoretical framework for evaluating the effects of different degrees of node cooperation on the performance of DTN routing protocols. The first part of the work assumed a fully cooperative node behavior and presented an analytical characterization of the performance of Epidemic and Two-Hop routing in terms of packet delivery ratio. These results were then used in the second part of the work to analytically characterize the performance of Epidemic under different degrees of node cooperation. The third part of the work presented a simulation study, which evaluated the performance of Epidemic, Two-Hop, and Binary Spray and Wait protocols under different degrees of node cooperation. The observed results showed that Binary Spray and Wait has the better resilience to lower node cooperation, while presenting the best compromise between packet delivery ratio and message overhead.

Altman [219] analyzed competitive and cooperative operation in DTNs considering a Two-Hop routing strategy. The effect of competition between network nodes was studied in a game theoretical setting. Insights into the structure of equilibrium policies were provided as well as a comparison to a cooperative scenario.

Solis *et al.* [220] presented a work related to this area of research. The work introduced the concept of “resource hog” as a DTN network node that, on average, attempts to send more of its own data and possibly forward less peer data than a typical well-behaved node. Moreover, a “malicious resource hog” may accept all incoming messages sent by the peer nodes, but immediately drop them. A performance evaluation through simulation revealed that the delivery ratio of well-behaved nodes decreases significantly in the presence of a reduced number of nodes acting as resource hogs. The work also proposed and evaluated resource management solutions to deal with the “resource hogs” problem.

2.3.5. Queuing Disciplines

As previously discussed, the effective operation of a DTN relies on the cooperation of network nodes to store-carry-and-forward bundles. In addition, routing protocols may perform bundle replication to discover more possible paths, and thus increase the bundle delivery rate and decrease the bundle delivery delay. However, the problem is that the combination of bundle storage during long periods of time and their replication leads to high storage and bandwidth overhead. As network nodes have limited resources, this may degrade the overall network performance.

As part of the resource allocation mechanisms, each DTN node must implement some queuing discipline that governs how data bundles are buffered while being carried and waiting to be transmitted. This queuing discipline, illustrated in Figure 2.17, consists of both a scheduling and a dropping policy. The scheduling policy determines the order in which bundles are transmitted at a contact opportunity. The dropping policy selects bundles to be dropped upon buffer overflow.

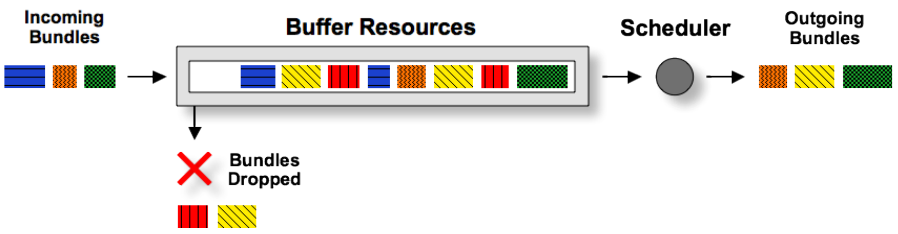

Figure 2.17: Illustration of a queueing discipline composed by a scheduling and a dropping policy.

Previous research has demonstrated that scheduling and dropping policies play an important role in the performance of delay-tolerant networks. Lindgren and Phanse [221] compared the performance of Epidemic and PRoPHET routing protocols when different combinations of queuing and forwarding policies were used. They showed that these policies could optimize the limited system resources utilization, leading to performance improvement of the routing protocols, in terms of message delivery, overhead, and end-to-end delay. They also concluded that when bandwidth is limited, it is not enough to decide which messages should be forwarded but also the order in which they must be forwarded.

Zhang *et al.* [201] presented an analysis of buffer-constrained Epidemic routing. Simple buffer management policies were evaluated. The authors concluded that with adequate buffer management schemes, smaller buffers could be used without negative impact on the delivery ratio observed with this routing protocol.

Krifa *et al.* [222] also based their study on Epidemic routing. The authors considered the theory of encounter-based message dissemination to propose an optimal buffer management policy based on global knowledge about the network. This policy can either maximize the delivery probability or minimize the average delivery delay.

Erramilli and Crovella [223] observed that it is important to study forwarding and dropping policies independently of each other. The focus of their work was on comparing message prioritization schemes for transmission or dropping that do not take into account network information with schemes based on delegation forwarding algorithms [224]. The authors concluded that the latter schemes performed better in terms of delivery rate, delay and cost. Based on their results, the authors also stated that forwarding policies have less impact in the network performance than dropping policies.

Li *et al*. [225] studied the impact of buffer management strategies under Epidemic routing. They proposed a congestion control mechanism called N-Drop. This policy takes into account the number of times a message has been forwarded and a threshold related to the size of the buffer, to decide which messages should be dropped when buffer overflow occurs.

2.4. Summary

This Chapter reviewed the state of the art in vehicular networking in Section 2.2. Topics that were covered included the design challenges, applications, research projects, and architectures. Particular attention was given to the analysis of traditional routing strategies for vehicular networks and the motivation for the use of DTN techniques. Following from this, Section 2.3 overviewed the state of the art in delay-tolerant networking, focusing on DTN architecture concepts, application scenarios, and routing protocols. Other topics also reviewed included stationary relay nodes, cooperation, and queuing disciplines. These topics are of particular interest to this thesis and will for that reason be further discussed in the next Chapters.

Chapter 3

Vehicular Delay-Tolerant Networks

3.1. Introduction

This Chapter presents the main contribution of this thesis, a vehicular network architecture that presents unique properties for enabling delay tolerant communications in sparse or partitioned opportunistic vehicular networks, called vehicular delay-tolerant networks (VDTNs).

The outline of this Chapter is as follows. Section 3.2 presents the VDTN layered architecture, including the definition of its network elements, as well as its layered networking model and the data transmission method. Section 3.3 addresses the issue of using node localization information for allowing contact duration estimation and to predict the maximum number of bytes that is possible to transmit. Section 3.4 defines traffic differentiation mechanisms for VDTNs, describing buffer management strategies and dropping policies with distinct approaches to buffer space allocation and contention resolution, and scheduling policies with different solutions to the traffic prioritization problem. In Section 3.5, a new geographic routing protocol for VDTN networks, called GeoSpray, is presented. The main conclusions of this Chapter are presented in Section 3.6.

Part of this Chapter was published in [36-39, 50, 54-56].

3.2. A Layered Architecture for Vehicular Delay-Tolerant Networks

Before presenting the VDTN network architecture proposal, it is important to illustrate a scenario in which a VDTN is used and describe the role of the network nodes. Depending on the network application scenario, the following fixed and mobile nodes can be considered in a VDTN: terminal nodes, mobile nodes, and stationary relay nodes. The interactions between these network nodes are illustrated in Figure 3.1.

Terminal nodes are fixed nodes that are the access points to the VDTN network, thus acting as traffic sources and sinks. Mobile nodes (i.e., vehicles) are opportunistically exploited to collect and disseminate data. They move on roads and carry data that must be delivered to the terminal nodes. Stationary relay nodes are fixed devices with store-and-forward capabilities that are located at road intersections. Mobile nodes use them to deposit and pickup data. As previously discussed in Subsection 2.3.3, stationary relay nodes increase the number of contact opportunities in scenarios with low node density. Thus, they can contribute to increase the data delivery probability and to decrease the average delivery delay. It is important to note that in some deployment scenarios, a VDTN network may be composed, for instance, of only mobile and relay nodes. In such scenarios, the final applications run on the mobile nodes. Thus, besides carrying data, the mobile nodes will also act as traffic sources and sinks.

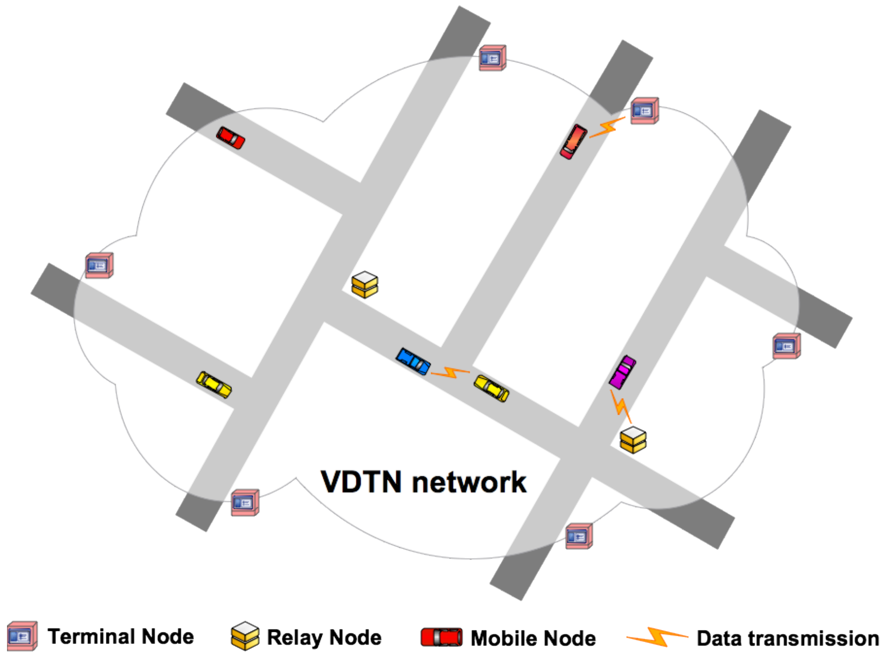

Figure 3.1: Illustration of VDTN network nodes.

The vehicular delay-tolerant network layered architecture follows the open systems interconnection (OSI) reference model [27, 28] from the International Organization for Standardization (ISO) [226] and the transmission control protocol/Internet protocol (TCP/IP) architecture [59, 227, 228]. Figure 3.2 shows the VDTN protocol layers, in comparison with OSI model, TCP/IP, and DTN architectures.

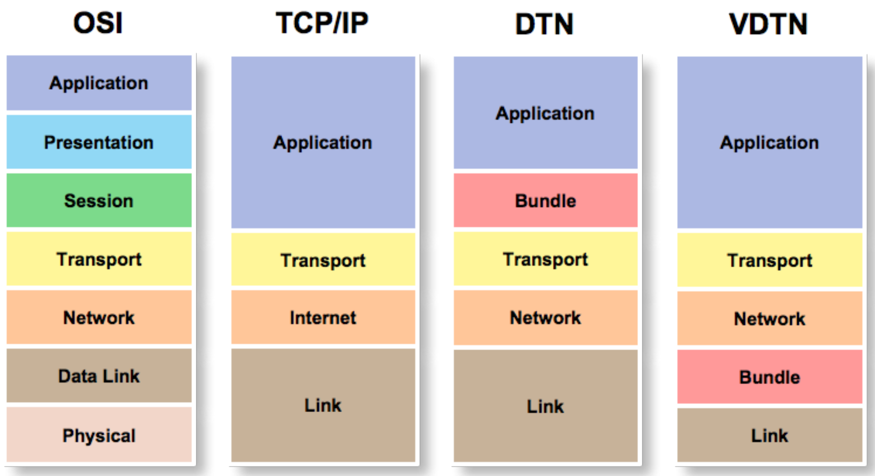

Figure 3.2: Comparison of OSI, TCP/IP, DTN, and VDTN protocol layers.

From Figure 3.2 it is possible to observe that DTN architecture [21] builds a store-and-forward overlay network introducing a bundle layer that operates over different transport and lower layer protocols. As discussed in Section 2.3, DTN architecture allows using optimized network stacks to tackle the characteristics of heterogeneous networks deployed in extreme environments (e.g., an interplanetary network or a sensor network), and interconnects them using asynchronous message switching. On the contrary, the VDTN architecture places the VDTN-based bundle layer below the network layer introducing an IP over VDTN approach. The motivation for this approach is as follows. First, as stated in [31], DTN architecture departs from the Internet model that is defined by the end-to-end use of Internet protocol (IP) [30] rather than bundling. The benefits of maintaining end-to-end IP communication semantics are evident, since it facilitates seamless interoperability with existing networks (i.e., the seamless extension of the Internet) and can provide interoperability with some Internet applications. Moreover, no protocol translation gateways are needed.

Second, as stated in [32], it can be observed that IP itself provides asynchronous packet delivery mechanism and that IP packet delivery can be delayed if applications tolerate large delays and asynchronous communications. Therefore, the use of UDP-based or UDP-like asynchronous communication protocols in the upper layers can be combined with addressing the disruption and disconnection interruption issues at the VDTN layer. This approach enables IP over VDTN architecture to support a class of vehicular network applications characterized by delay tolerant, asynchronous data traffic. Such applications can even tolerate some data loss.

VDTN bundle layer also defines the “bundle” as its protocol data unit (PDU). However, in the case of VDTN architecture, a bundle consists of an aggregate of IP packets with common attributes (e.g., destination address and quality of service). The aggregation of IP packets to form the payload of data bundles is expected to result in fewer packets processing and routing decisions, which can be translated to less complexity, faster routing, lower network cost, and energy savings. Even though it is assumed that the access network connected to the VDTN is an IP network, this architecture is general enough to support any other network layer protocol. In addition, since VDTN technology is comprised only in the two lower layers of the OSI model this also leads to a simpler and faster processing of protocol data units.

Figure 3.3 details the VDTN layered architecture that introduces the notion of control plane and data plane separation, supporting out-of-band signaling. In other words, in VDTN networks, the data plane assembles, transmits, and processes the data bundles (DBs), while the control plane is responsible for the transmission and processing of control bundles (CBs). The CBs are used to convey signaling information such as requests, responses and status information, and precede the transmission of DBs. A variety of signaling functions is performed to establish, maintain, and terminate connections that are used for data bundles transmission. The use of distinct planes suggests that they can operate independently using their own layers and protocols (i.e., a separate protocol stack is used for each plane). Therefore, the DBs and CBs can be transmitted out-of-band using different transmission technologies that best suit their needs. Moreover, data and control plane separation provides more flexibility in designing protocols on both of them. The VDTN architecture concepts of control and data plane separation together with data packets aggregation under the network layer are conceptually similar to optical burst switching (OBS) [229-231].

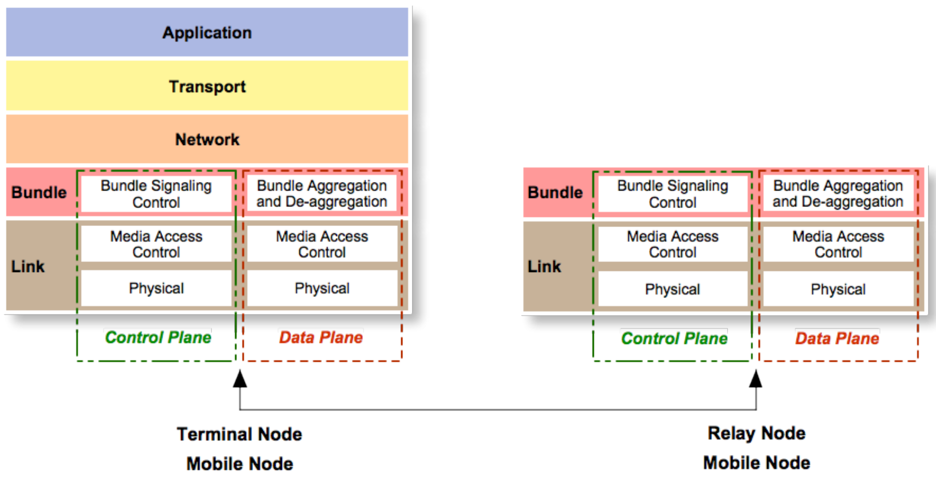

Figure 3.3: IP-over-VDTN layered architecture.

An interesting characteristic of VDTN architecture is that network nodes do not need to implement all protocol layers. As illustrated in Figure 3.3, because applications run on terminal nodes, they must implement all the layers of the VDTN protocol stack. Moreover, since terminal nodes are able to do heavy data processing, they can implement more complex functions and services. On the contrary, due to possible constraints, relay and mobile nodes may implement only the lower layers, offering simpler functions. It is also possible for a mobile node to implement the full protocol stack if the final applications run on vehicles. This approach allows the bundles to be quickly processed and transmitted over the network. Network intelligence will be concentrated at the edge of the network.

Next Subsections present the basic functionalities of each layer of the data and control planes. The layered architecture of each plane is described, starting with the data plane.

3.2.1. Data Plane

The data plane is responsible for the transport of incoming packets, which are aggregated into data bundles, from a source node to a single or multiple destination nodes. Hence, the functions executed at this plane deal with data bundles and include, among others, buffer management (queuing), scheduling, traffic classification/differentiation, data aggregation/de-aggregation, and forwarding.

3.2.1.1. Bundle Aggregation and De-aggregation Layer

Following DTN architecture, VDTN also implements a store-carry-and-forward bundle delivery paradigm based on persistent storage, to cope with intermittency, partition, disconnection and long delays. This paradigm, illustrated in Figure 3.4 and described in Section 2.3, is implemented in the bundle aggregation and de-aggregation layer (BAD).

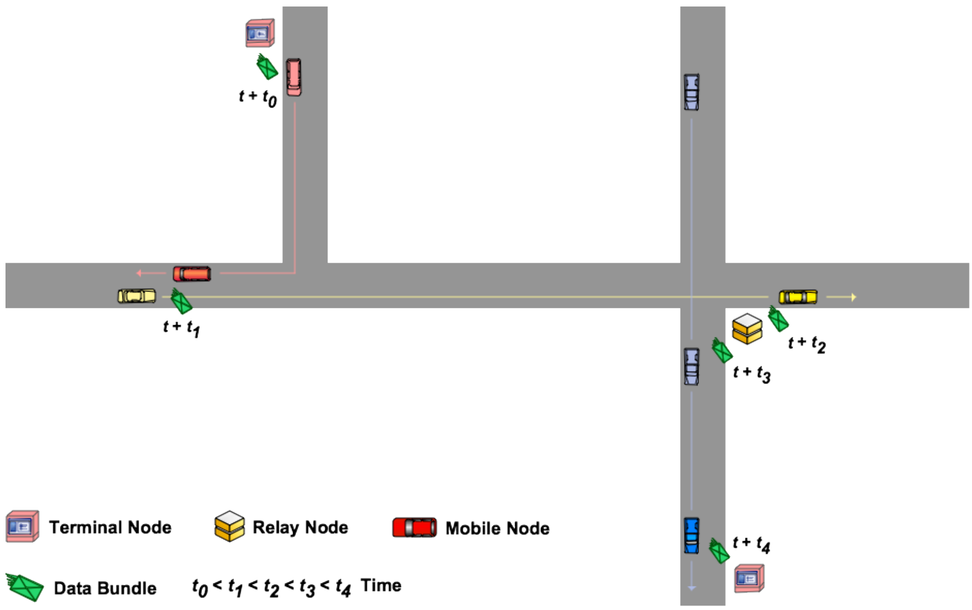

Figure 3.4: Illustration of the store-carry-and-forward paradigm in a VDTN network.

At the source terminal node (i.e., ingress edge node), the BAD layer is responsible for aggregating and assembling network layer protocol data units (e.g., IP packets) with common properties to form a data bundle payload. The bundle is then transmitted over a VDTN network, from source to destination node(s), via a store-carry-and-forward approach that may involve several intermediate nodes (Figure 3.4). At the destination terminal node, this layer does the reverse process, de-aggregating received DBs into individual IP packets. This process is illustrated in Figure 3.5.

Several techniques may be considered for the assembly process. In application-based bundle assembly, a data bundle is created by the aggregation of IP packets that carry data to the same destination application. Another criteria for bundle assembly can be based on quality of service (QoS) issues, which can be used for traffic prioritization (discussed below in Section 3.4). Under this technique, IP packets with the same quality of service requirements are aggregated together. Another possibility is aggregating packets for the same destination node irrespective of the final application. Bundle assembly techniques must take into account a size threshold that establishes a limit to the maximum number of IP packets contained inside the payload of a bundle. Timer-based approaches may also be considered (alone or in conjunction with other above-presented criteria) in order to define the time interval between bundle generations. It is important to note that bundle aggregation process can be further refined with the use of summarization functions [232]. Such functions can rely on the analysis of data requests similarities, to reduce the amount of data carried by the VDTN network.

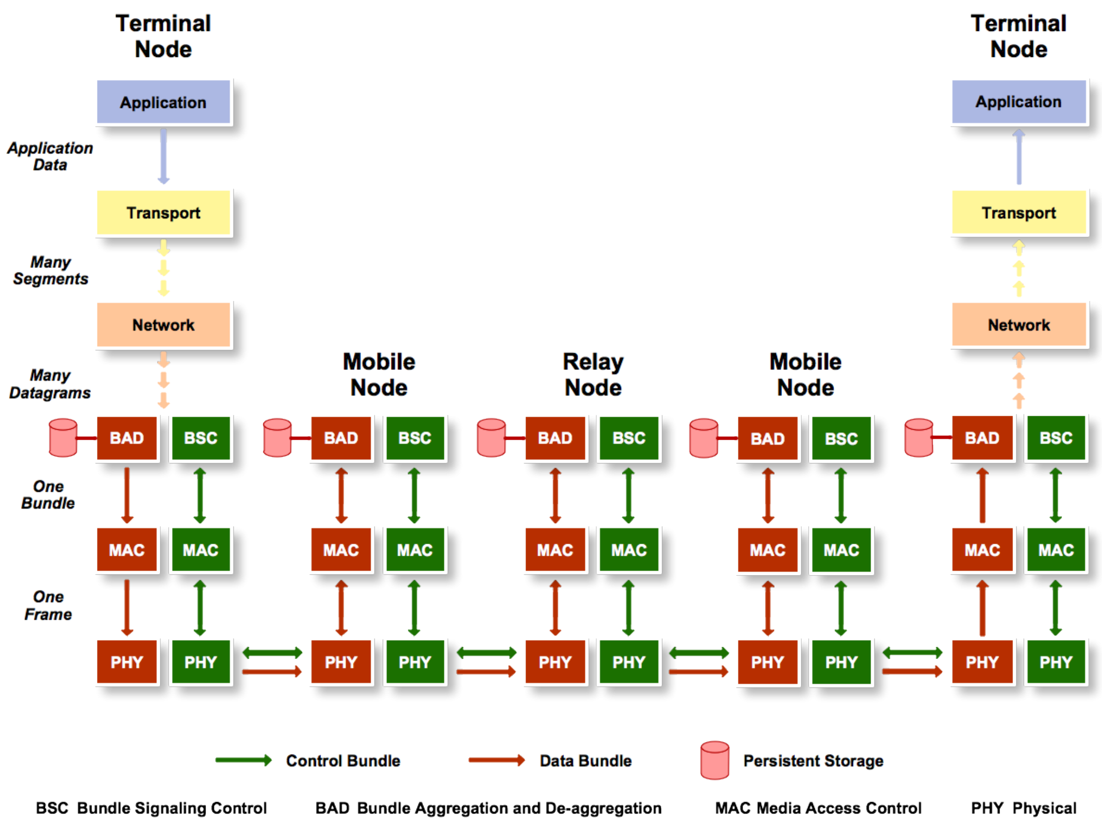

Figure 3.5: Example of the transmission of control bundles and data bundles, between network nodes, from a source to a destination.

DTN custody transfer mechanism [21] is also the proposed reliability scheme for VDTN architecture and it is implemented at the BAD layer. As explained in Section 2.3, custody transfer uses hop-by-hop reliability to enhance end-to-end reliability. However, it does not provide guaranteed end-to-end reliability. This can only be accomplished if a source node requests both custody transfer and return receipt.

To prevent the carriage of unauthorized traffic, it is necessary to authenticate and authorize network nodes. Furthermore, the DBs and CBs integrity also needs to be protected. Confidentiality issues also arise in these networks. The radio link technologies native security mechanisms may be insufficient to obtain these security requirements. Thus, some of the security mechanisms proposed for DTN networks [21, 190, 233, 234] and vehicular ad hoc networks [66, 69, 70, 79], can be incorporated at this layer. However, it is important to notice that security deployment increases processing costs and also has a negative impact on energy savings.

If different radio link technologies, with its correspondent maximum transmission units (MTU), are used for the DBs transmission, then DBs can be fragmented while in transit. Fragmentation can also occur when a bundle is only partially transmitted. Therefore, at the final destination the BAD layer is responsible for reassembling the fragments, as well as executing re-sequencing (sequencing verification). The default size for a data bundle is based on the MTU of the link technology used.

Due to the higher bit error rates in vehicular communications (compared with wired networks), BAD layer should also provide the means to detect and correct corrupted data on incoming data bundles. For example, if flooding based routing is used, it can cause a situation where more than one copy of a particular DB arrives at the destination node. Even if all of these copies are corrupted, their combined information can be used to correct or minimize errors, obtaining as much error free information as possible. Power constraints make this function only available at mobile nodes, and eventually, in terminal nodes.

3.2.1.2. Media Access Control Layer

The media access control layer (MAC) provides functional and procedural means to transfer data between VDTN network nodes in point-to-point and point-to-multipoint communications. In addition to framing and media access control, this layer contains flow control mechanisms that are used between network nodes, to pace the rate at which DBs are transmitted. Although the MAC layer may provide the possibility to detect and eventually correct errors that may occur in the physical layer (PHY), these functions may not be desirable at this layer and therefore may only be performed at the BAD layer.

The wireless link technologies that are used to support the transmission of DBs provide specifications for the two lower layers of the OSI reference model. Thus, each technology has its specific MAC and PHY layers. Some examples of technologies that have been considered for vehicular communications include IEEE 802.11a/b/g [101], dedicated short range communications (DSRC) [235], 802.11p/WAVE (wireless access in vehicular environments) [236, 237], and cellular technology (2/2.5/3G). It is also possible to consider a scenario where VDTN nodes have more than one of these technologies available. In this case, the exchange of control information (CBs) will allow to decide what link technology will be employed at a particular contact (established between two network nodes) to exchange data bundles.

Wireless link technology or technologies available in the network nodes will be chosen based on the following criteria: node type (e.g., mobile, stationary, terminal), node design (e.g., power constraints, speed), link characteristics (e.g., bandwidth, transmission range, power consumption, error rate), and economical considerations.

3.2.1.3. Physical Layer

The physical layer is responsible for the actual transport of data bundles from one network node to another. Even though physical layer functions are essential for the overall performance of the link technology, since they are part of the implementation of a specific wireless link technology, it is not relevant to discuss them in this context.

3.2.2. Control Plane

As above-mentioned, the separation between data and control planes in vehicular delay-tolerant networks was inspired by the possibility of network nodes to exchange control information at the connection setup phase. In addition, the control plane and data plane separation allows both planes to evolve independently. Hence, new specifications, functions and services can be deployed at one of these planes, without having to change the other one.

The control plane includes, among others, signaling, routing, node localization (i.e., contact duration estimation), resources reservation (at the data plane), and other network protocols that are used to set up, maintain, and terminate data plane connections.

3.2.2.1. Bundle Signaling Control Layer

The bundle signaling control layer (BSC) provides a signaling protocol for use at the connection setup phase. This protocol allows network nodes to exchange signaling messages in the form of control bundles. These CBs include information such as, but not limited to, node type, geographical location, route, speed, supported link technologies properties (e.g., range, data rate), energy status, buffer status, bundle sizes, delivery options, routing state information, and security requirements, among others. The control plane uses this information to perform functions related with reserving, configuring, maintaining, and terminating data plane connections. This approach is used to optimize data bundle transmission, performed at the data plane level.

The importance of BSC layer on the overall network performance motivates the necessity for introducing security mechanisms at the control plane that allow to control the integrity of signaling messages and verify their origin. Previous discussion on data plane security issues is also valid here.

3.2.2.2. Media Access Control and Physical Layers

In general, it is assumed that control bundles have a small size and require low bandwidth. Consequently, in a scenario where a node has support for different wireless link technologies, CBs can be carried out-of-band through a separate, dedicated, low power, low bandwidth, and long-range link. This link must always be active to allow node discovery. On the contrary, the data plane can use a high-power, high bandwidth, and short-range link to exchange data bundles. The data plane link connection will be active only during the estimated contact duration time. This will be discussed in the next Section.

The principle of out-of-band signaling is illustrated in Figure 3.6. At the time $t+t_0$, two network nodes detect each other and start exchanging signaling messages through the control plane link connection. Based on this information, the data plane connection is configured and activated on both nodes at the time $t+t_1$. Then, the data bundles are forwarded until the time $t+t_2$. The data plane connection is deactivated after this time because the nodes are no longer in the data plane link range of each other.

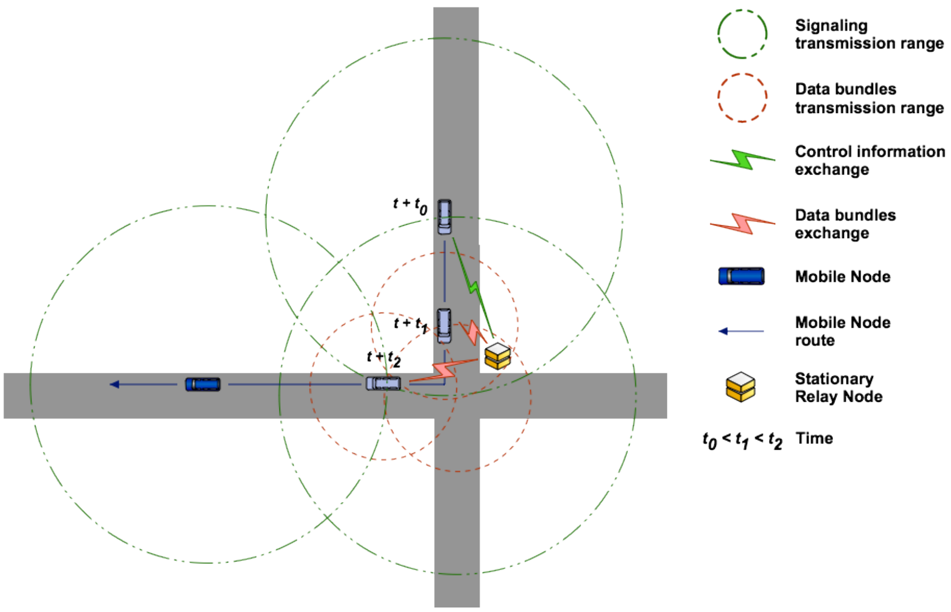

Figure 3.6: Illustration of control information and data bundles exchange between network nodes.

Furthermore, it should also be noted that the processing of signaling information might allow concluding that a contact opportunity should be ignored, and thus the data plane link should not be activated. Such situation may occur, for example, *i)* if the predicted contact duration is too short for a successful bundle transmission; *ii)* if the data plane link radio cannot be activated in time; *iii)* if there are not any data bundles to be exchanged between the network nodes (this will differ according to the routing protocol being used); *iv)* if a node has energy constraints; or *v)* to prevent buffer overflow and thus avoid bundle drops and unnecessary resources consumption.

The separation between control and data planes with out-of-band signaling, is considered very important because it not only ensures the optimization of the available data plane resources (e.g., storage and bandwidth) [50], but also allows to save power, which is very important for energy-constrained network nodes such as stationary relay nodes [37, 238].

The above-mentioned information about link technologies for the data plane, and their MAC and PHY layer functionalities and procedures, remains valid here. Therefore, these layers are not further discussed.

3.3. Exploiting Node Localization

During a contact opportunity, if nodes are not aware of the contact duration, they may start transmitting data bundles whose size exceeds the maximum number of bytes that can be transmitted before the available link is terminated. This results in incomplete bundle transmissions, as illustrated in Figure 3.7. If bundle fragmentation and reassembly [21] are not allowed, then the partially transferred bundles are discarded, causing the waste of data link capacity and, eventually, energy resources [146].

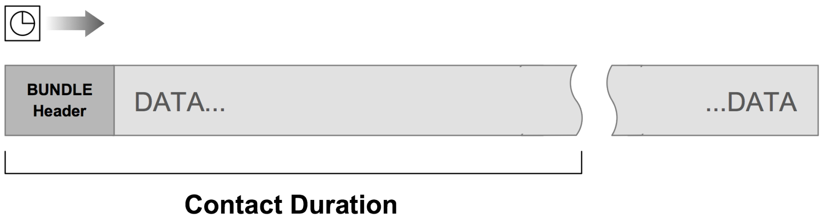

Figure 3.7: Illustration of an incomplete bundle transmission.

As explained in the previous Section, in a VDTN, the cooperative exchange of node localization information at the control plane, can be explored to predict the period of time during which the nodes' data plane links will be in range with each other [50]. A contact prediction algorithm (CP) executed at the control plane is responsible to provide this function. CP assumes that network nodes have access to a location service based on position information derived using global positioning system or other similar system. It also assumes that the following attributes are included on control messages: geographical position, path (i.e., route, trajectory), and speed. The CP algorithm uses this signaling data in conjunction with map information to predict the topology holes (i.e., the space without connectivity) that might exist due to the spatial constraints of nodes movement. Therefore, CP estimates the period of time during which nodes are within communication range, i.e., the contact duration. Next, the theoretical analysis of the calculation of contact duration is presented.

In this analysis it is assumed that during the time that lasts the contact, the mobile nodes maintain a constant speed (*v*), do not change their direction, and maintain the same distance while passing in different lanes (*d*). It is also assumed an omnidirectional (circular) transmission range (*r*) and that there are no obstacles blocking the data transmission.

Four different types of opportunistic contacts can occur in a vehicular delay-tolerant network. Figure 3.8 *(A)* represents the case where two mobile nodes (i.e., vehicles) approach an intersection from different roads at the same time. If both mobile nodes are equally far apart from the intersection when the contact begins (i.e, the distance between them is below *r*), then Equation 3.1 can be used to calculate the contact duration (*Cdur*).

$$Cdur = \frac{2\sqrt{2}r}{v_1 + v_2} \tag{3.1}$$

Figure 3.8 *(B)* illustrates a situation where a mobile node passes by a stationary relay node. It is worth to notice that this type of contact can also occur when a mobile node passes by a terminal node or a stopped mobile node. Equation 3.2 can be used to calculate the contact duration in this type of contact.

$$Cdur = \frac{2\sqrt{r^2 - d^2}}{v_3} \tag{3.2}$$

In Figure 3.8 *(C)* two mobile nodes are moving in the same direction in a lane. Depending on their speed two situations can occur. If the mobile nodes move at the same speed, then the contact can last indefinitely. Otherwise, one mobile node may overtake the other. In this case, the contact duration can be calculated as described in Equation 3.3.

$$Cdur = \frac{2r}{|v_5 - v_4|} \tag{3.3}$$

Figure 3.8 *(D)* shows an example of a case where two mobile nodes are about to pass each other in opposite directions. In this case, the contact duration can be calculated according to Equation 3.4.

$$Cdur = \frac{2\sqrt{r^2 - d^2}}{v_6 + v_7} \tag{3.4}$$

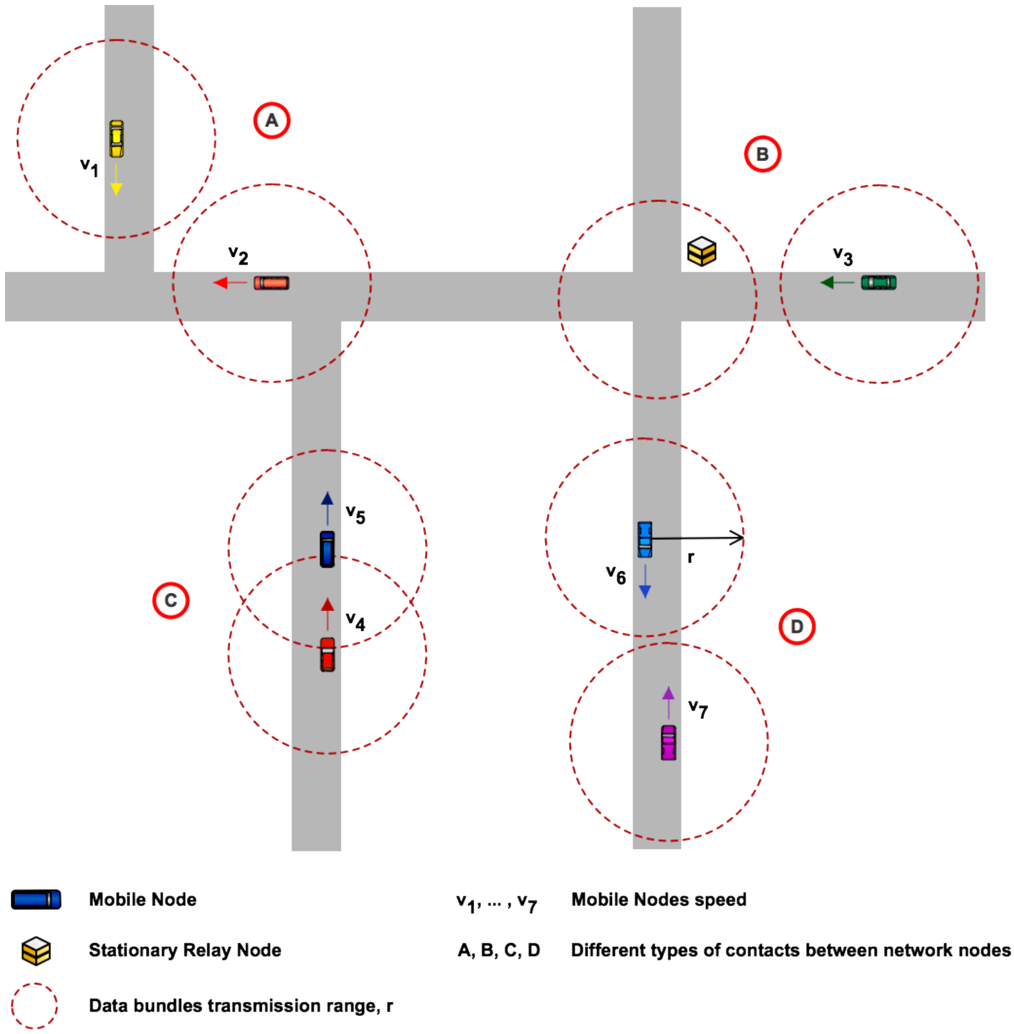

Figure 3.8: Illustration of different types of contacts between network nodes in VDTNs.

The information about contact duration can be used in conjunction with the information about the data plane link data rate to determine the maximum amount of data that can be transmitted on a contact, i.e., the contact volume. Hence, the contact volume (*Cvol*) can be defined as the product of the contact duration (*Cdur*) and the data plane link data rate (*Drate*), as shown in Equation 3.5.

$$Cvol = Cdur \times Drate \tag{3.5}$$

A scheduling policy can use the information about the contact volume to schedule a set of bundles whose size does not exceed the estimated maximum number of bytes that can be transmitted. Intuitively, the use of this approach will result in increasing the number of successfully relayed data bundles at contact opportunities. Thus, the bandwidth utilization in the data plane connections is improved. Furthermore, this may also contribute to increase the bundles delivery probability and to decrease their average delivery delay.

In addition, the use of the information about contact duration and contact volume, together with the remaining signaling information, enables the decision module, illustrated in Figure 3.9, to decide whether to ignore or accept a contact opportunity. Recall that, as discussed in Section 3.2, a contact opportunity may be ignored, for example, if the predicted contact duration is too short for a successful bundle transmission, if the data plane link radio cannot be activated in time, if a node has energy constraints, if there are not any bundles to be exchanged between the network nodes, or to prevent buffer overflow and thus avoid bundle drops and unnecessary resources consumption.

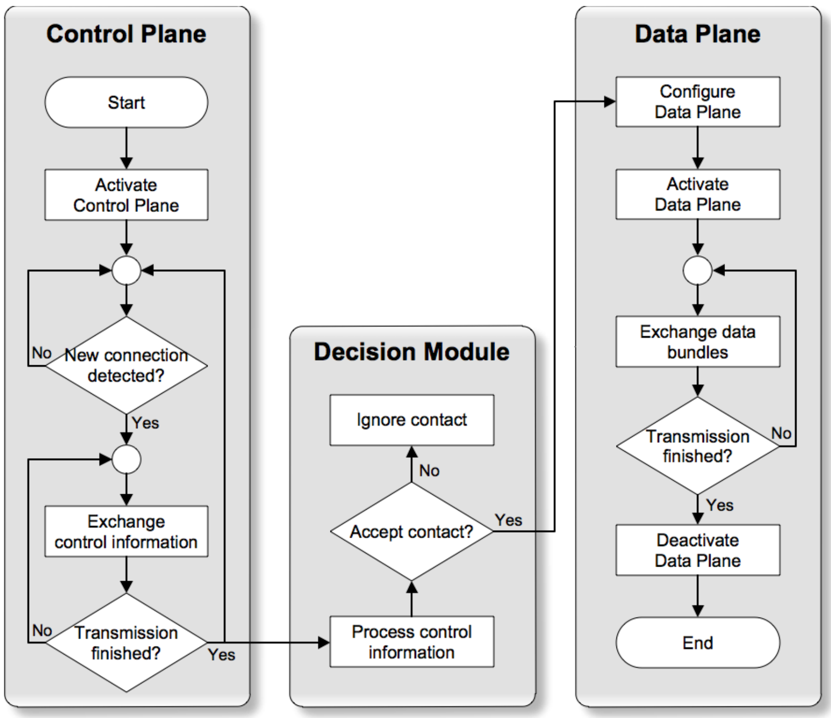

Figure 3.9: Flowchart describing control plane and data plane interaction, coordinated by the decision module.

The contact duration time can also be used to determine the time when the data plane link should be activated and deactivated. Figure 3.10 is used here for the illustration of this concept. While moving along its path, a mobile node uses its control plane connection to detect the presence of another network node and to discover its characteristics. The mobile node receives the information that the peer node is a stationary relay node. The control information exchanged between these nodes allows to obtain information about the geographical position of both nodes, the point coordinates along the vehicle's route (x_i,y_i), the vehicle's velocity (v), the transmission range (r_d) and data rate, among others. This data can be used to compute the distance (d_{A-D}) to be traveled by the vehicle until it intersects the stationary relay node, as shown in Equation 3.6. Then, this information allows calculating the contact duration (*Cdur*), as presented in Equation 3.7.

$$d_{A-D} = \sum_{i=0}^{1} \sqrt{(y_{i+1} - y_i)^2 + (x_{i+1} - x_i)^2} \tag{3.6}$$

$$Cdur = \Delta t_{A-E} - \Delta t_{A-C} = \frac{d_{A-D} + r_d}{v} - \frac{d_{A-D} - r_d}{v} = \frac{2 \times r_d}{v} \tag{3.7}$$

The data plane link needs to be activated when the mobile node is in the position *C* (Figure 3.10). The distance traveled by the mobile node until that position can be calculated by Equation 3.8. Using this information, it is possible to determine the number of seconds (*Tact*) that the mobile node requires to travel to position *C*, as given by Equation 3.9. Likewise, the predicted time at which the data plane link should be deactivated (*Tdeact*) is given by Equation 3.10.

This approach contributes to reduce the power consumption of the high-powered and high bandwidth data plane link, which is very important for network nodes with limited energy resources like stationary relay nodes and terminal nodes in rural connectivity scenarios.

$$d_{A-C} = d_{A-D} - r_d \tag{3.8}$$

$$Tact = \frac{d_{A-C}}{v} \tag{3.9}$$

$$Tdeact = \frac{d_{A-D} + r_d}{v} \tag{3.10}$$

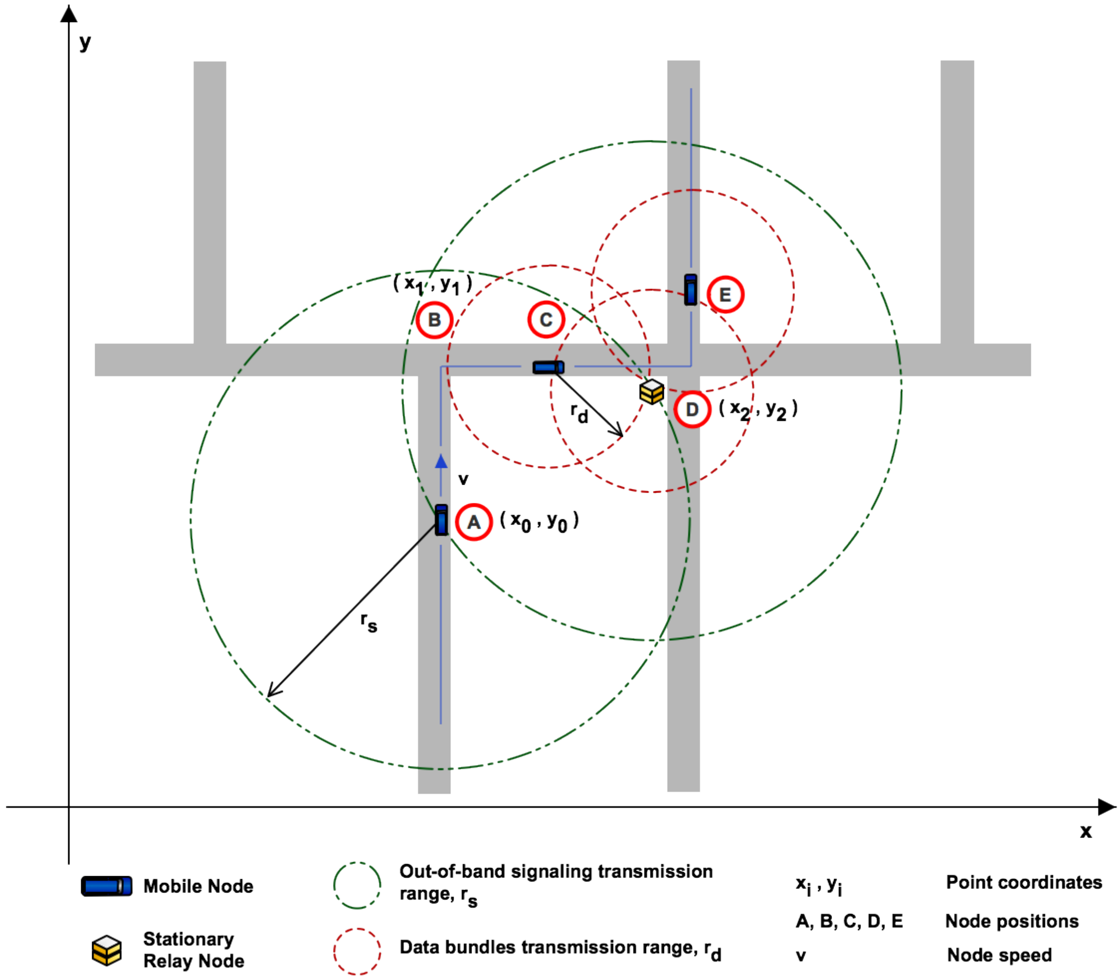

Figure 3.10: Prediction of contact duration and data link activation and deactivation time.

3.4. Traffic Differentiation Support

Vehicular delay-tolerant networks can be used in a broad range of real world application scenarios, including to disseminate information advertisements or safety related information, or as monitoring networks to collect data. In fact, multiple applications can be supported simultaneously on a VDTN network. For instance, one can envision a scenario where a VDTN is opportunistically exploited to transport data from an emergency dissemination information application and from a monitoring pollution data collection application. Each of these applications generates data bundles with different requirements. An application for emergency dissemination information is better served by minimizing delivery delay (since the information becomes quickly outdated), whereas an application for monitoring pollution data collection is better served by maximizing bundle delivery probability.

The traditional “best-effort” store-carry-and-forward service is not adequate in such a scenario where multiple non-real time applications, with different performance requirements, compete for scarce network resources. In a best-effort model, all traffic is treated in the same manner, regardless of its type. Bundles are handled according to a first-in, first-out (FIFO) policy, as represented in Figure 3.11. Thus, bundle scheduling and dropping decisions are only based on the criteria of bundle arrival time (to the nodes' buffers) with no guarantee of service quality.

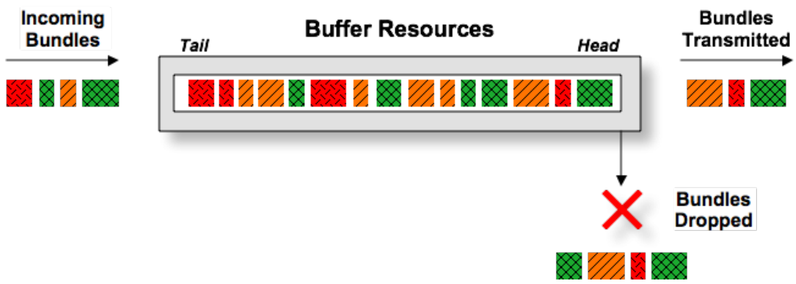

Figure 3.11: Illustration of FIFO policy.

This Section addresses this problem, integrating traffic differentiation mechanisms in vehicular delay-tolerant networks, as illustrated in Figure 3.12. In order to provide traffic differentiation at the VDTN bundle layer, network traffic must be classified and marked according to a priority classes-of-service scheme. In addition, buffer management strategies, scheduling and dropping policies with support to traffic prioritization must be enforced across all network nodes. Next Subsections discuss these concepts.

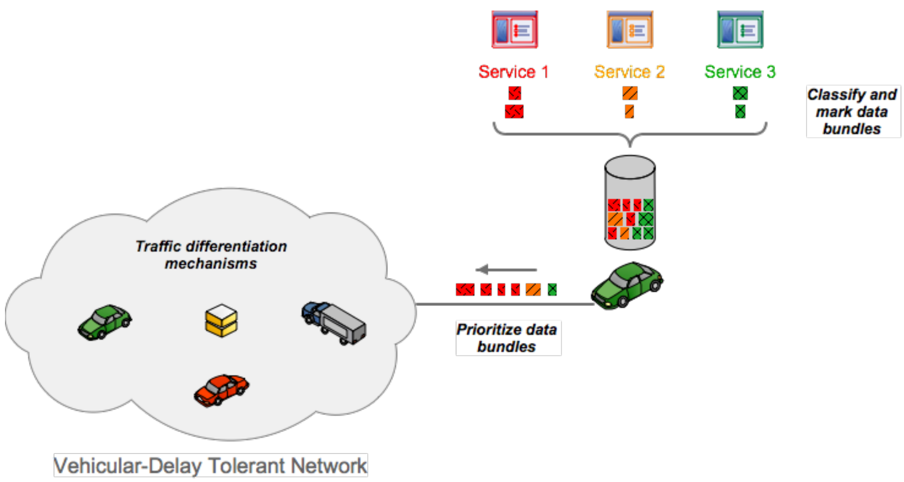

Figure 3.12: Illustration of traffic differentiation in vehicular delay-tolerant networks.

3.4.1. Data Bundles Classification and Marking

Source nodes are responsible to classify and mark data bundles. Classification is the first stage to implement differentiated services. Several criterions can be used to classify data, such as source application, delivery urgency, IP destination addresses, IP type of service (TOS)/differentiated services code point (DSCP), among others. Each of these criteria can be used separately or in conjunction with one another. Classification identifies traffic that will map to each priority class and, according to VDTN architecture proposal, traffic that belongs to the same class can be aggregated into data bundles [37]. Following the classification criteria, data bundles that belong to priority classes are marked accordingly.

A priority classes of service (CoS) model is considered, similar to the one proposed for the DTN architecture [21]. Therefore, data bundles can be marked as bulk (lowest priority), normal or expedited (highest priority), based on their delivery urgency. In addition, it is assumed that bundles priorities are time invariant [239], and that bundles' (initial) priority class cannot be reclassified again by any network node.

3.4.2. Buffer Management Strategies

Network nodes provide traffic differentiation by processing incoming and outgoing data based on the bundles' priority class marking. This processing involves performing per-hop actions like buffering, dropping, and scheduling. This Subsection discusses the strategies for buffer space management considered in this work.

The first approach, illustrated at Figure 3.13, considers that all bundles share the same buffer space. Since preference is given to high priority classes, in cases of buffer congestion, the drop policy selects lower priority bundles to be discarded first. The buffer space occupied by these bundles is used to store higher priority ones. In a scenario with stringent storage constraints where network applications generate high rates of expedited bundles, these bundles may monopolize all the network storage resources. Thus, preventing bulk and eventually normal priority bundles of being stored, carried, and forwarded between nodes.

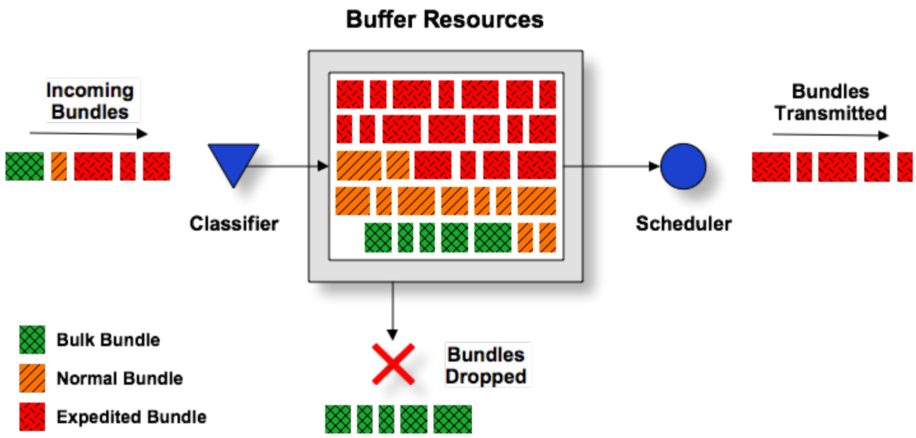

Figure 3.13: Operation of a common buffer for all priority classes.

Another approach for buffer management based on priority classes, is presented in Figure 3.14. This second strategy proposes the creation of a separate queue for each priority class. The length (i.e., size) allocated in each queue for bundles is related to each priority class. The queue for expedited bundles is greater than the queue for normal bundles and this queue is also greater than the queue for bulk bundles. Network nodes indentify and classify the incoming data bundles, and store them in the corresponding queue. When there is no space available in a certain queue of a given priority class to store an incoming data bundle, the drop policy only discards bundles from that queue (until there is enough space available). This approach guarantees that network nodes can store and carry bundles of all priority classes at all times, independently of the storage constraints, and the expedited and normal bundles generation rates.

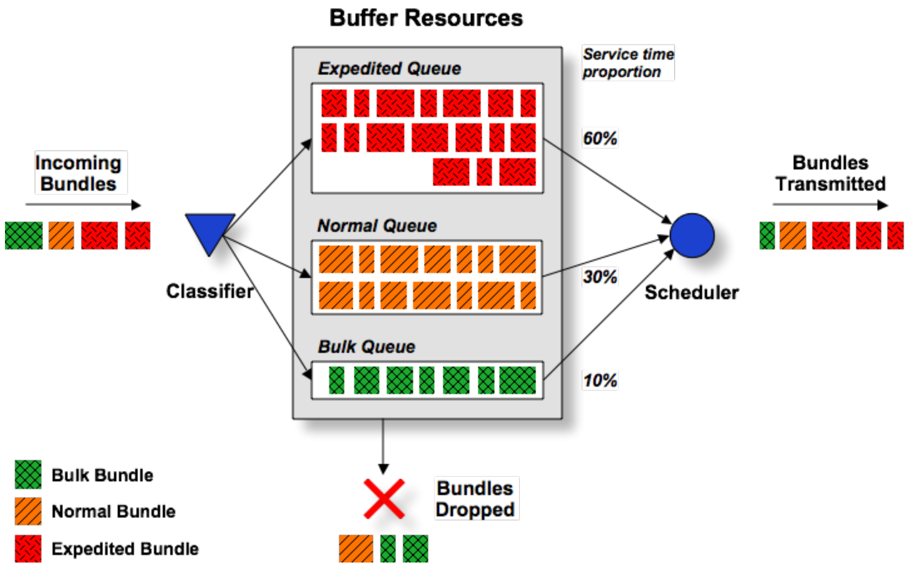

Figure 3.14: Operation of separate queues for each priority class.

3.4.3. Scheduling Policies

In order to achieve traffic differentiation, the above-mentioned buffer management strategies and drop policies must work together with scheduling policies designed to support traffic prioritization. The following priority class scheduling policies are considered: Priority Greedy and Custom Service Time.

Priority Greedy (PG) scheduling policy strictly complies with the priority class sequence from high (expedited) to low (bulk). At a contact opportunity, higher priority class bundles are always scheduled before lower priority ones. Hence, higher priority bundles may monopolize the network resources (e.g., bandwidth and storage) and lower priority bundles may be severely delayed. In fact, these bundles may never get served in scenarios with limited network resources and short contact duration times. This scheduling policy is illustrated in Figure 3.13. As may be seen, due to a short contact duration between nodes, only expedited bundles were served and transmitted.

Custom Service Time (CST) scheduling policy uses the estimation about contact time duration provided by the VDTN control plane [37, 50], as discussed in Section 3.3. CST assigns service time percentages to each of the priority classes, as illustrated in Figure 3.14. At a contact opportunity, the contact duration estimation is used in conjunction with the service time percentages to calculate the periods of time during which bundles from each priority class are transmitted.

When there are no bundles of a certain priority class available at the node's buffer, the service time assigned to this priority class is used by the next one with lower priority. Moreover, while dispatching bundles of a certain priority class, if the remaining service time is insufficient to transmit any bundle stored in this queue, this time is used for transmitting bundles from the next lower priority queue. The Custom Service Time operating principle not only ensures expedited bundles can get more service time but also prevents normal and bulk bundles from not being served at all (Figure 3.14).

3.5. GeoSpray: A Geographic Routing Protocol for VDTNs

This Section presents GeoSpray, a multiple-copy geographic routing protocol designed for VDTNs. This protocol exploits the mobility of vehicles and the location information provided by positioning devices, such as GPS, to assist routing decision-making process, according to a store, carry, and forward paradigm. GeoSpray is intended to be used on sparse, opportunistic vehicular scenarios where communication opportunities are based on sporadic and intermittent contacts, frequent link disconnections and reconnections occur, and the probability of forming a contemporaneous multi-hop path between the source and the destination is negligible. The next Subsection describes the operation details of GeoSpray protocol. The protocol design and its pseudo-code are presented in Subsection 3.5.2.

3.5.1. Protocol Operation

The GeoSpray routing protocol assumes that all VDTN network nodes are aware of their location (geographical position) that is provided by a positioning device like a GPS [130] navigation system. This system includes a GPS device, a map, and it is able to calculate the route, distance, and time between two map points. It also assumes that location of terminal nodes (traffic sinks) is previously known, and that mobile nodes know their speed and current route/path. It is important to notice that bundles replicated or forwarded following the routing decisions of GeoSpray represent aggregates of datagrams that are destined for the same terminal node (traffic sink).

GeoSpray is inspired in the general guidelines of GeOpps geographic forwarding routing protocol [25], which was presented in Subsubsection 2.3.2.1. It uses geographic position information and other mobility parameters, together with bundle destination addresses, making sure that bundles are forwarded towards the destination. However, contrary to

GeOpps that maintains at most one copy of a bundle in the network, GeoSpray combines selected replication and forwarding with explicit delivery acknowledgments.

The GeoSpray routing protocol employs the concept of “spray phase” from Binary Spray and Wait [202] to minimize the spraying time [202, 240], where a small/fixed number of bundle copies are distributed to distinct nodes in the network (as described in Subsubsection 2.3.2.2). However, instead of doing blind replication (as proposed in Spray and Wait), GeoSpray guarantees that bundle copies are only spread to network nodes that go closer (and/or arrive sooner) to the bundle’s destination. Furthermore, instead of waiting until one of these nodes meets the destination node and delivers its bundle copy (as proposed in the Spray and Wait “wait phase”), GeoSpray allows each node to forward its bundle copy further to another node that can take the data closer to the destination (or sooner in time).

GeoSpray provides robustness by allowing a limited number of copies of the same bundle to be routed independently. The protocol controls flooding by setting an upper bound on the number of copies created per bundle, while minimizes the transmission overload and resources consumption. Furthermore, GeoSpray uses the concept of active receipts presented in [241] to explicitly clear delivered bundles. Network nodes send receipts to inform all the nodes they meet about bundles that have already been delivered. These bundles copies, which are buffered at intermediate nodes, are removed and the storage capacity for upcoming bundles is improved. This is a very important feature because network nodes have limited storage capabilities. Moreover, it also helps to stop replicating/forwarding already delivered bundles, thus also saving bandwidth resources.

Figure 3.15 presents a unified modeling language (UML) [242] activity diagram that illustrates the operations performed by GeoSpray when two nodes meet each other in the network. Note that operations are mirrored between both nodes. As expected, routing information exchanged at the control plane is used in conjunction with other signaling information for resource allocation at the data plane level. More data plane resources (e.g., storage and bandwidth) are allocated to bundles that will be carried more close to their destination and that have been less replicated.

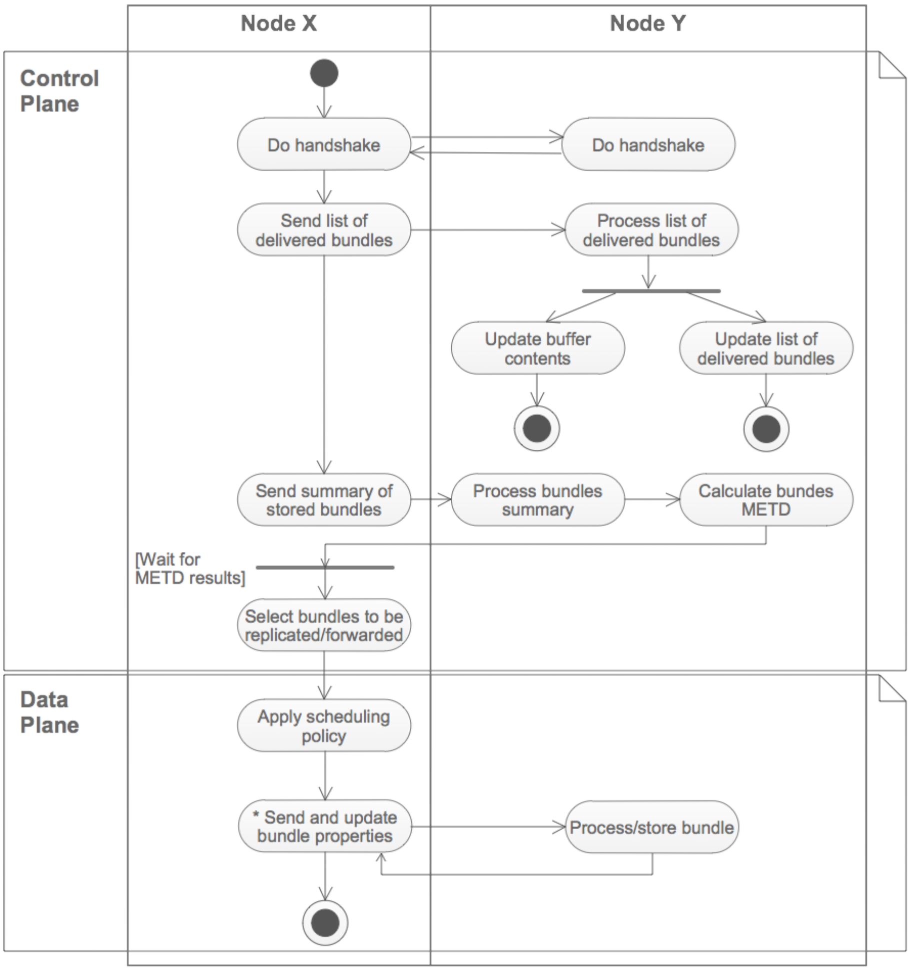

Figure 3.15: UML activity diagram describing the sequence of main actions executed in GeoSpray when two nodes exchange data among them.

As a conclusion, GeoSpray fuses several control data sources to perform routing decisions. Figure 3.16 shows the fusion scheme, with the above-explained different data sources. The source control data "minimum estimated time of delivery" may combine information about vehicles routes with their average speed to compute a utility function that puts emphasis on distance or delay [25]. As a result, "greater quality" information for this routing metric is obtained. Furthermore, source control data, such as "location information", can be the result of information fusion, as may be seen in [243]. It elaborates on how information provided by a number of localization techniques (e.g., GPS, map matching, dead reckoning, cellular localization, image/video processing, localization services, and relative distributed ad hoc localization) can be combined to compute a more accurate position for vehicles.

The "GeoSpray routing algorithm" block works combining information from several data sources to perform the appropriate routing decisions. Further details about data-fusion can be found in [232].

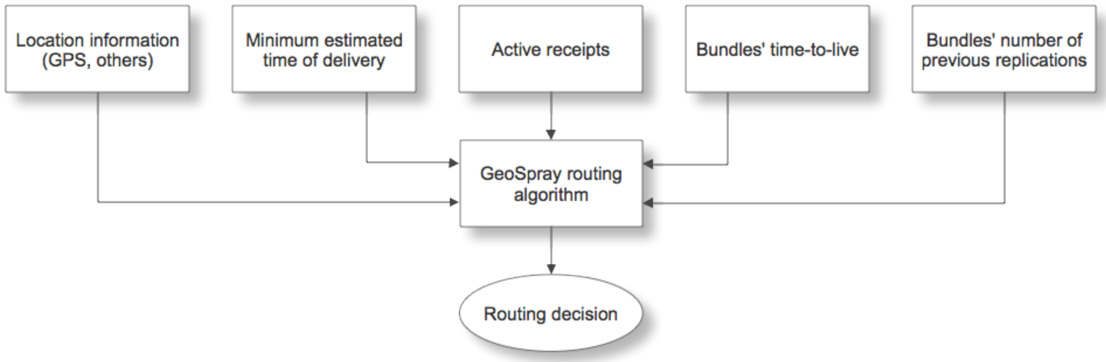

Figure 3.16: Routing control data-fusion model for GeoSpray.

3.5.2. Protocol Design

The GeoSpray protocol operation described in the previous Subsection is presented here in Figure 3.17, in the form of a pseudo-code that describes the sequence of steps executed at a node *X* when a new contact opportunity is detected with node *Y*. The protocol is symmetric. Hence, *Y* executes the same sequence of steps. As expected, these steps involve the interaction between the control plane and the data plane.

In the first step, *X* sends to *Y* a list containing information about the bundles that it knows that have been delivered in the network. This information includes the identification, source and destination addresses, and a hash of the content of each known delivered bundle, among others. Based on the same type of information received from *Y*, *X* deletes any bundles stored in its buffer that *Y* announces as delivered. Then, *X* updates its list of delivered bundles with the information received from *Y* in order to notify other nodes at future contact opportunities.

The second step executed in *X* consists in checking if *Y* is the final destination for any of the bundles stored in *X's* buffer. If that happens, these bundles are scheduled to be transmitted first to *Y*, followed by the remaining bundles sent in an order determined by the execution of the next steps. As expected, bundles whose final destination is *Y* after being delivered are removed from *X's* buffer and are added to *X's* list of delivered bundles.

The third step involves selecting the best carrier for each bundle stored in *X* and *Y*. *X* sends to *Y* a list containing information about the bundles that it stores. This information includes the identification, source and destination addresses, size, TTL, number of copies (L), hash of the content, and *X's* minimum estimated time of delivery (METD) of each bundle, among others. METD is a concept introduced by GeOpps, which was described in Subsubsection 2.3.2.1 and it is calculated as proposed in [25]. Based on the same type of information received from *Y*, *X* calculates the METD that it requires to deliver each bundle stored by *Y* that they do not have in common. This information is sent to *Y*. *X* also receives from *Y* its calculation of the METD for *X*'s bundles.

In the fourth step, *Y's* calculation of the METD for *X's* bundles is used at *X* to decide which bundles should be sent to node *Y*. *X* only replicates/forwards the bundles for which *Y* will be closer to their destination or sooner in time (i.e., the *Y*'s METD value for these bundles is lower than *X*'s METD). A bundle selected to be transmitted to node *Y* is: *i)* replicated if *X* carries more than one copy of that bundle, thus handing half of the remaining copies to *Y* (Binary Spray and Wait [202] described in Subsubsection 2.3.2.2); or *ii)* forwarded to *Y* and removed from *X's* buffer (because *X* carries only one copy left of that bundle). It is assumed that each bundle has a header field indicating the "number of copies" it represents. As expected, the actual bundle is not replicated within *X's* buffer.

The fifth and final step is required because of the restricted amount of data that can be transferred at a given contact opportunity. Due to short contact durations and limited bandwidth, it may not be possible to transfer all the bundles stored in *X* that node *Y* can carry closer to their destination or deliver earlier. Therefore, there is the need for scheduling data bundles for transmission based on their *METD*, *L*, and *TTL* header field parameters, as shown in Figure 3.18. As expected, data bundles that have the lowest METD are the first to be transmitted (METD ASC). When two bundles have the same METD value, the tie is broken by first scheduling the bundle that has been less replicated (RC ASC). A secondary tiebreak criterion is applied for bundles that have the same METD and have been replicated the same number of times. In such cases, bundles with longer remaining TTLs are scheduled to be sent first (RL DESC). Regarding this issue, Section 6.5 will discuss why the combination of RC ASC and RL DESC scheduling policies improves the network performance in terms of the bundle delivery probability and the bundle average delivery delay.

Protocol GeoSpray (X,Y)

1. Explicitly clear delivered bundles:

- Send to *Y* information about the *X's* list of known delivered bundles.
- Receive information from *Y* about its list of known delivered bundles.
- For each bundle *i* stored in *X*'s buffer
  - If *i* is in *Y's* list of known delivered bundles, delete *i*.
- Update *X's* list of known delivered bundles, by merging *X* and *Y* information.

2. Delivery to final recipient:

- For each bundle *i* stored in *X*'s buffer and destined to *Y*
  - *X* delivers *i* to *Y*, and deletes *i* from its buffer.
  - *X* adds *i* to its list of known delivered bundles.

3. Carrier choice:

- Send information to *Y* about the bundles stored in *X's* buffer.
- Receive information from *Y* about the bundles stored in its buffer
  - For each bundle *i* stored in *Y's* buffer
    - If *i* is already in *X*'s buffer, ignore *i*.
    - Else
      - Calculate the METD required by *X* to deliver *i* to its destination.
      - Include this information in *i*.
- Send information to *Y* about *X's* METD for *Y's* bundles.
- Receive information from *Y* about its METD for *X's* bundles.

4. Replication/forwarding decisions:

- For each bundle *i* in *X's* buffer
  - If *i* is already in *Y's* buffer, ignore *i*.
  - Else if *X's i* METD > *Y's i* METD
    - If the remaining number of copies (*L*) of *i* > *1*
      - *X* hands over to *Y* *L*/2 copies of *i*.
    - Else
      - *X* forwards *i* to *Y*, and deletes *i* from its buffer.

5. Schedule bundles for transmission:

- Bundles selected to be replicated/forwarded to *Y* are arranged in ascending order of their METD (METD ASC). The tiebreaker rules are: (1) smaller number of replications (RC ASC), (2) longer remaining TTL (RL DESC).

Figure 3.17: GeoSpray protocol pseudo-code.

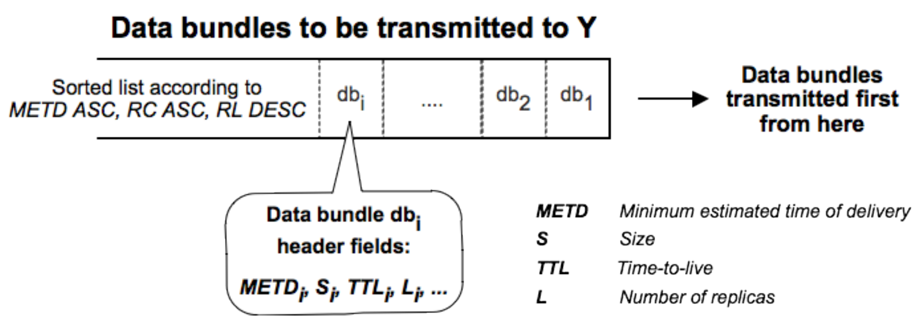

Figure 3.18: Position of data bundle *i* in a queue of data bundles to be transmitted from the node *X* to the node *Y*.

3.6. Summary

In this Chapter a new network architecture for vehicular networks was proposed. The vehicular delay-tolerant network layered architecture, presented in Section 3.2, attempts to provide a solution to the technical challenges caused by the properties of vehicular networks, and by a variety of factors including node heterogeneity, node interactions, node cooperation, and limited network resources. The VDTN layered architecture is a novel approach of a delay-tolerant network that gathers contributions from other technologies, such as OBS, cooperative and opportunistic networks. It follows the store-carry-and-forward paradigm proposed for DTNs, however, on contrary to DTN architecture, which introduces the overlay bundle layer over the transport layer to allow the interconnection of highly heterogeneous networks, VDTN architecture places the bundle layer below the network layer, thus introducing an IP over VDTN approach. Another distinctive characteristic of VDTN architecture is the proposal of out-of-band signaling with separation of the control and data planes. The use of out-of-band signaling procedures ensures the optimization of the data plane resources and also allows saving power, which is very important for power-limited network nodes. The VDTN architecture layers were named and defined, and the features of the protocols that are likely to reside in each layer were described and discussed.

Section 3.3 explored the characteristics of control plane and data plane separation, studying the advantages of introducing the function of node localization at the control plane. It was shown that the exchange of signaling information related to nodes' real-time location, current route/path, speed, and transmit range, can be used to estimate contact durations. Then, contact duration information can be used in conjunction with signaling information about the link data rate to predict the maximum number of bytes that can be transmitted during contact opportunities. This allows preventing incomplete bundle transmissions, optimizing data plane link utilization. Moreover, the information about contact duration can be used to determine the period of time when the data plane link should be activated. This approach allows extending battery life of power-limited network nodes, like relay nodes.

Section 3.4 has explored different ways to implement traffic prioritization on VDTN networks. A priority classes of service model was considered. It was analyzed how different buffer management strategies can be combined with dropping and scheduling policies, to provide strict priority based services or to provide custom allocation of network resources.

This Chapter also presented the proposal of a geographic routing protocol for VDTN networks, called GeoSpray. This contribution, presented in Section 3.5, comes from the analysis of the existing popular (i.e., widely applicable) routing protocols for DTN-based networks, taking into account their operation, implementation and relative performance, discussed in Chapters 2, 4, 5 and 6. GeoSpray takes routing decisions based on geographical location data, and combines a hybrid approach between multiple-copy and single-copy schemes. First, it starts with a multiple-copy scheme, spreading a limited number of bundle copies, in order to exploit alternative paths. Then, it switches to a forwarding scheme, which takes advantage of additional contact opportunities. To improve resources utilization, delivered bundles are cleared across the network nodes.

Chapter 4

Design and Implementation of a Simulation Tool and a Laboratory Testbed for VDTNs

4.1. Introduction

The implementation and deployment of vehicular delay tolerant networks poses a number of technical challenges due to the unique properties of these networks and to a variety of factors including, but not limited to, node heterogeneity, node interactions, node cooperation, and limited network resources. Three main research methods can be used to assist the development, evaluation, diagnose, and validation of protocols, algorithms, services, and applications for these networks: theoretical analysis, simulation, and reproduction in a testbed [244-246].

The theoretical analysis is characterized by the use of mathematical constructs and models to assess the network performance. Unfortunately, finding the right mathematical constructs to represent a VDTN is very difficult and they can get very complex for realistic considerations. Simulation tools provide a highly flexible, low-cost, and rapid mean to allow research questions and prototypes to be explored. Moreover, simulation offers a high degree of control and repeatable experiments to the researchers. Both theoretical analysis and simulation tools typically abstract many details of the reality. These simplifications often lead to results that may not fit with real-world measurements. Therefore, to confirm the validity of the theoretical analysis and simulation results, experiments should be conducted on a testbed. Usually this is done through the creation of a prototype. The prototype should represent the real environment, in order to find results and conclusions that can be transferred to a real deployment.

This Chapter presents a simulation tool and a laboratory testbed created to support the research work carried out on behalf of this thesis. The Chapter is organized as follows. Section 4.2 describes the design and implementation of a simulation tool for VDTNs, called VDTNsim. A map-based model representation of Portugal's *Serra da Estrela* Region is also presented in this Section. This map-based model is considered important as it provides the basis to study the behavior of VDTNs on rural connectivity scenarios considered in Chapter 5. Section 4.3 presents the design and implementation of a laboratory testbed for VDTNs, called VDTN@Lab. Finally, Section 4.4 summarizes the Chapter.

Part of this Chapter was published in [40-44].

4.2. Design and Implementation of a Simulation Tool

Although several simulation tools are currently available for VANETs (a survey may be found in [67]) and for DTNs (such as, DTNSim [194], DTNSim2 [247], Pydtn [248], VNUML [249], and ONE [250-252]), simulating a VDTN is fundamentally different in that it considers a distinct approach towards vehicular data communication, as discussed in the previous Chapter. Therefore, the proposal of VDTNs and their layered architecture created the need for developing a simulation tool that models the behavior of this network architecture to allow the study and performance analysis of protocols, algorithms, services, and applications for these networks.

Rather than building a simulator from scratch, which requires a considerable programming effort and is time-consuming, it was considered preferable to use an existing validated simulator and specialize it. Hence, it was decided to adapt/extend the source code of a well-known DTN simulator, to create a simulation tool for VDTNs, which was named VDTNsim. VDTNsim is built up on the core of the Opportunistic Network Environment simulator (ONE) version 1.3.0 [250-252], which is presented next.

4.2.1. Opportunistic Network Environment Simulator

The ONE was developed on behalf of the SINDTN and CATDTN projects supported by Nokia Research Center (Finland) and on the TEKES ICT-SHOK Future Internet project. It is an agent-based discrete event simulator that has been used in many DTN research works, which is constantly updated with new features. Briefly, this simulator is able to *i)* generate node movement using different internal and external movement models; *ii)* support different node types; *iii)* support different DTN routing schemes; *iv)* display real time information related to bundle (i.e., message) transfer and node movement in a graphical user interface; and *v)* produce reports about nodes movement, bundle passing, and general statistics. Complete details about this simulator are provided in [250, 252] and its Java [253] source code is freely available for download at [251].

It was decided to change and extend this DTN simulator instead of a VANET simulator because the ONE implements the DTN store-carry-and-forward routing paradigm, which is essential to the vision of the proposed VDTN architecture. Moreover, the ONE implements the algorithms of six DTN routing protocols described in Subsection 2.3.2: Direct Delivery [196], First Contact [194], Epidemic [200], Spray and Wait [202], PRoPHET [203], and MaxProp [24].

The ONE also offers support for several synthetic vehicular mobility models like random map-based movement (MBM), shortest path map-based movement (SPMBM), and route map-based movement (RMBM). MBM model can be used to simulate mobile nodes moving randomly along the roads defined by the map data. In the SPMBM model, mobile nodes choose a random point on the map or a point from a list of points of interest (that can model real-world destinations such as tourist attractions, shops, or restaurants) as their next destination, and then follow the shortest path/route from their current location. RMBM model allows simulating mobile nodes that follow pre-determined routes like bus, tram, or train routes. Furthermore, the simulator offers map data of the Helsinki (Finland) downtown area (i.e., roads) that these three map-based movement models can use. Besides implementing these mobility models, ONE also provides interfaces for loading movement data generated by external programs or obtained from real-world GPS traces.

This simulator allows the creation of simulation scenarios where there are groups of nodes of different types with distinct characteristics (e.g., mobile or fixed) and capabilities (e.g., storage space, radio bit-rate and range). This feature allows the representation of the VDTN network nodes (terminal nodes, stationary relay nodes, and mobile nodes). It is even possible to have in the same simulation scenario groups of mobile nodes that follow different mobility models, or groups of nodes that use different routing protocols and/or different scheduling and dropping policies.

4.2.1.1. Graphical User Interface of the ONE Simulator

The main window of the ONE's graphical user interface (GUI) is shown in Figure 4.1. This GUI allows the observation of a simulation in real-time. It is possible to observe specific details, such as the simulation events (e.g., contact start/finish times and bundle creation/deletion/transfer times) (Figure 4.1), the number of bundles carried by nodes, nodes current locations and their path (Figure 4.2), and the connections occurring between nodes (Figure 4.3). Selecting a node from the list available at the main GUI, allows the analysis of further information about the number of bundles carried by it and about the routing module's state (e.g., successful delivered bundles, active connections, incoming/outgoing bundles). This information is shown in Figure 4.4.

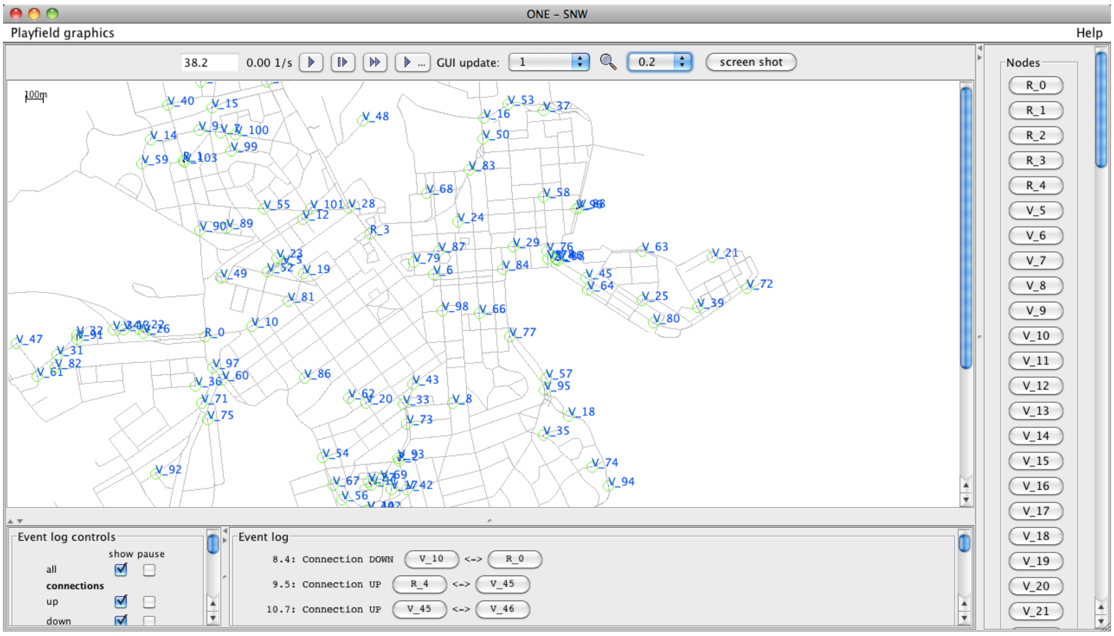

Figure 4.1: Screenshot of the ONE simulator's graphical user interface.

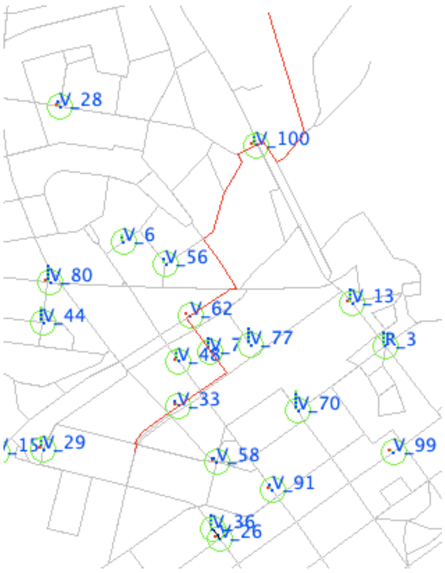

Figure 4.2: Detail of a mobile node's current location and its path.

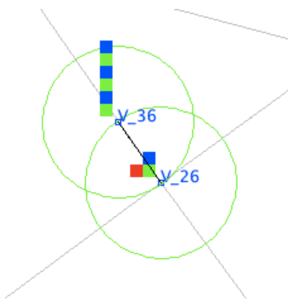

Figure 4.3: Detail about two nodes carrying and exchanging bundles.

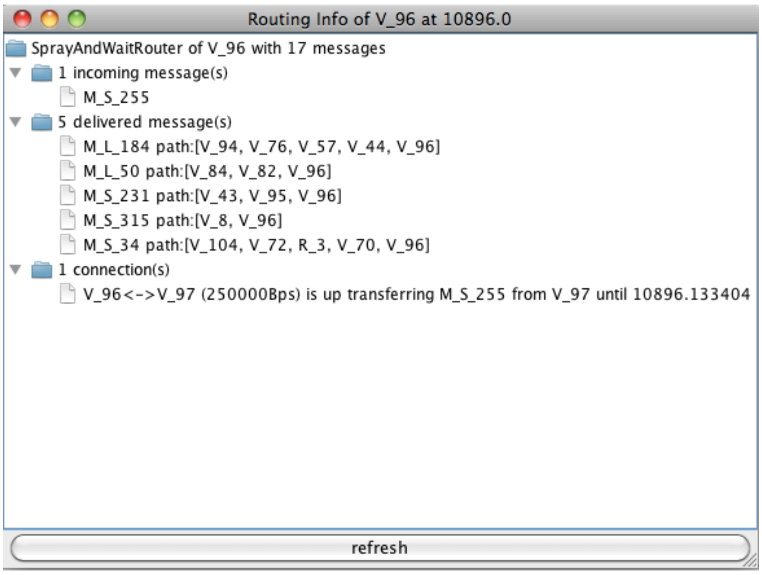

Figure 4.4: Detail providing information about a node's routing module.

The simulator can be executed using the GUI (Figure 4.1) or in a batch mode. The batch mode, shown in Figure 4.5, does not start the GUI but displays information about the simulation progress on the terminal shell.

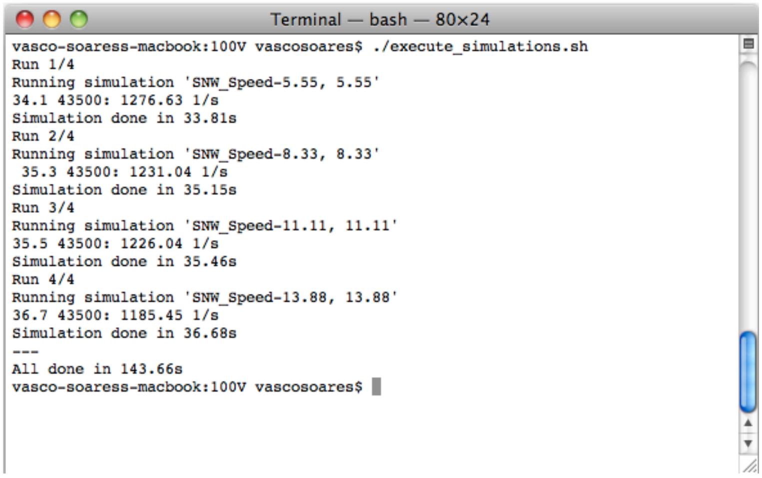

Figure 4.5: Screenshot of the ONE running simulations on a batch mode.

4.2.1.2. Scenario Generation

The ONE simulator reads the simulation parameters from a single or a set of input configuration files, which are regular text files that contain key-value pairs. An example of a part of the principal configuration file together with the corresponding explanation of each configuration parameter is shown in Figure 4.6. Further simulation parameters have been omitted for simplification purposes but do not affect the understanding of this description.

```
##########################################################
# SCENARIO SETTINGS
##########################################################
Scenario.name = SNW
Scenario.simulateConnections = true
# How many seconds are stepped on every update of the simulation
Scenario.updateInterval = 0.1
# How many simulated seconds to simulate, 43200 = 12 hours
Scenario.endTime = 43200
# Number of groups of nodes deployed in the scenario
Scenario.nrofHostGroups = 2

##########################################################
# NODE GROUP SPECIFIC SETTINGS
##########################################################
# groupID: Group's identifier
# nrofHosts: Number of hosts in the group
# transmitRange: Range of the hosts' radio devices (meters)
# transmitSpeed: Transmit speed of the radio devices (bytes per second)
# movementModel: Movement model of the nodes
# waitTime: Min and max wait times after reaching destination (seconds)
# speed: Minimum and maximum speeds (m/s) when moving on a path
# bufferSize: Size of the buffer (bytes)
# router: Routing protocol used to route bundles (i.e., messages)
# msgTtl: TTL (minutes) of the bundles
# okMaps: Which map nodes can be used by the nodes group (map file indexes)
# routeFile: Route's file path - for MapRouteMovement model
# routeType: Route's type - for MapRouteMovement model (e.g., 1 = circular)
Group.movementModel = ShortestPathMapBasedMovement
Group.router = SprayAndWaitRouter
# Settings for Spray and Wait routing scheme
SprayAndWaitRouter.binaryMode = true
SprayAndWaitRouter.nrofCopies = 16
Group.transmitRange = 30
Group.transmitSpeed = 562.5k
Group.msgTtl = 60
# Bundles that final recipient marks as delivered are deleted from buffer
Group.deleteDelivered = true

## Buffer management ##
# Scheduling policy
# 1: random (bundle order is randomized every time; default option)
# 2: FIFO (bundles received most recently are sent last)
Group.sendQueue = 2
# Dropping policy
# 1: receive time (bundles received less recently are dropped first; default
option)
```

```
Group.dropQueue = 1

# Stationary Relay Nodes
Group1.groupID = R_
Group1.bufferSize = 500M
Group1.movementModel = MapRouteMovement
# File that contains the positions of the relay nodes in the map
Group1.routeFile = ../../data/relay_nodes.wkt
Group1.routeType = 1
Group1.waitTime = 0, 0
Group1.speed = 0, 0
Group1.nrofHosts = 5

# Mobile Nodes - Vehicles
Group2.groupID = V_
Group2.bufferSize = 100M
Group2.okMaps = 1
Group2.waitTime = 300, 900
# 10 km/h = 2.7 m/s; 50 km/h = 13.9 m/s;
Group2.speed = 2.7, 13.9
Group2.nrofHosts = 100

##########################################################
# BUNDLE CREATION PARAMETERS
##########################################################
Events.nrof = 1
Events1.class = MessageEventGenerator
# Creating interval in seconds - one new bundle every 25 to 35 seconds
Events1.interval = 25,35
# Bundle sizes (bytes)
Events1.size = 250k,1M
# Range of bundle source/destination addresses
Events1.hosts = 5,105
# Bundle ID prefix
Events1.prefix = M_

##########################################################
# MOVEMENT MODEL SETTINGS
##########################################################
# Seed for movement models' pseudo random number generator (default = 0)
MovementModel.rngSeed = 12
# World's size for Movement Models (width, height; meters)
MovementModel.worldSize = 4500, 3400
# How long time to move hosts in the world before real simulation
MovementModel.warmup = 1000
```

```
##########################################################
# MAP BASED MOVEMENT - MOVEMENT MODEL SPECIFIC SETTINGS
##########################################################
MapBasedMovement.nrofMapFiles = 2
# Roads loaded to simulate the real-world map
MapBasedMovement.mapFile1 = ../../data/roads.wkt
MapBasedMovement.mapFile2 = ../../data/main_roads.wkt

##########################################################
# SIMULATION OUTPUT REPORTS
##########################################################
# How many reports to load
Report.nrofReports = 2
# Length of the warm up period (simulated seconds)
Report.warmup = 0
# Default directory of reports
Report.reportDir = reports/
Report.report1 = MessageStatsReport
Report.report2 = ContactsPerHourReport

(...)
```

Figure 4.6: Example of a simulation scenario configuration file.

4.2.1.3. Simulation Reports

The ONE generates several types of simulation reports that provide information about different kinds of statistics, such as bundle relaying performance, amount of bundles delivered *versus* time, node contact time, number of contacts registered per hour, inter-contact time, total amount of contact times among nodes, number of contacts that each node has had, etc. This simulation reports are saved in output files. Figure 4.7 shows an example of a report that generated statistics about bundle relaying performance after a simulation execution. Each performance metric is described.

```
Bundle (i.e., message) stats for scenario SNW

# Time when the simulation ended
sim_time: 43200.0000
# Number of unique created bundles (does not count replicates)
created: 4440
# Number of started transmissions (one bundle can cause several transmissions)
started: 45911
# Number of succeeded transmissions (one bundle can cause many of these)
relayed: 35554
# Number of aborted transmissions (i.e., due to intermittent connectivity)
aborted: 10355
```

```
# Number of bundles that were dropped because of buffer congestion
dropped: 31806
# Number of bundles that were removed after successful delivery
removed: 4055
# Number of bundles successfully delivered
delivered: 2546
# Bundle delivery probability
delivery_prob: 0.5734
# Bundle delivery probability for responses
response_prob: 0.0000
# How many extra successful bundle transfers were needed for each delivery
overhead_ratio: 12.9647
# Bundle average delay (average time between bundle creation and delivery)
latency_avg: 2028.5075
# Median value of bundle average delivery delay
latency_med: 2143.0000
# Average number of hop count between the source and the destination nodes
hopcount_avg: 2.0770
# Median value of hop count
hopcount_med: 2
# On average how long bundles stay in the buffer (from receiving/creating them
until they're dropped or removed)
buffertime_avg: 1631.6982
# Median value of average buffer time
buffertime_med: 1459.0000
# Average time since bundle creation, to receiving a response
rtt_avg: NaN
# Median value of round trip time
rtt_med: NaN
```

Figure 4.7: Bundle stats report from a simulation run.

4.2.2. VDTNsim Simulation Tool

Several extensions were developed for the ONE in order to modify and extend this DTN simulation environment for modeling the behavior of the VDTN architectural approach. Figure 4.8 presents a unified modeling language (UML) [242] deployment diagram that illustrates the interaction among the developed components to model the VDTN architecture in the ONE simulator, creating a simulation framework named VDTNsim. More specifically, it was necessary to modify the ONE simulator code to model the store-carry-and-forward overlay network below the network layer. Furthermore, new code was written to support control and data planes separation performing out-of-band signaling. This required the adaptation and implementation of the control plane functions provided by the bundle signaling control layer (e.g., signaling, geographic localization, resources reservation, and routing), and the data plane functions provided by the bundle aggregation and de-aggregation layer (e.g., buffer management, scheduling, traffic classification, aggregation/de-aggregation, and forwarding).

Out-of-band signaling was achieved by the creation of a feature that allows network nodes to have two wireless network interfaces, each one with different network characteristics (e.g., transmission range and data transfer rate). As described in the previous Chapter, the control plane may use one of these network interfaces whereas the data plane uses the other one.

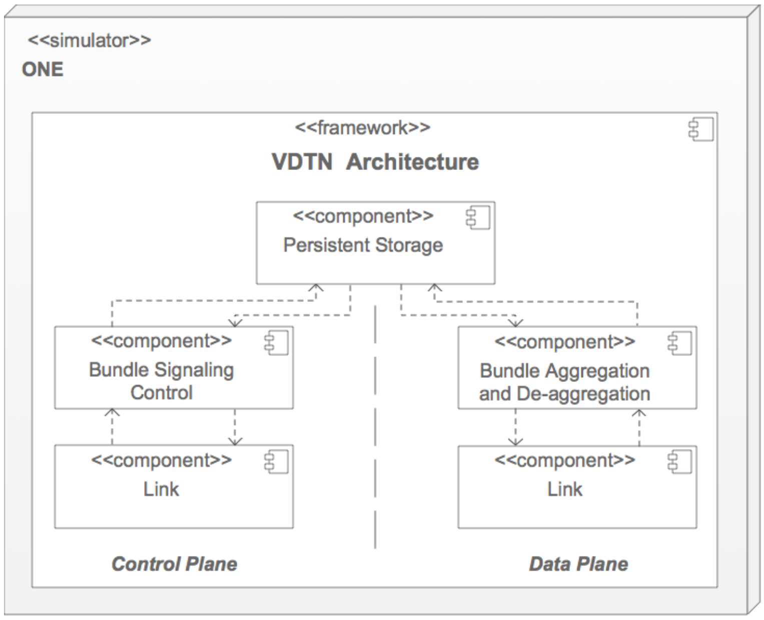

Figure 4.8: UML deployment diagram representing the implementation perspective of the VDTNsim framework in the ONE core simulator.

Figure 4.9 shows an UML class diagram that outlines the most important classes implemented in the VDTNsim and their relationships. Some details (e.g., class attributes and methods) are omitted to improve the figure readability. This comprehensive diagram provides an overview of the virtualization of the VDTN network model. The main class, called *VDTNHost*, interacts with the classes responsible for data exchange, which are the *ControlPlaneLink* (for signaling messages exchange) and the *DataPlaneLink* (for data bundles exchange). *VDTNHost* class also interacts with the classes that implement control plane (*BSC*) and data plane (*BAD*) separation. As expected, both *Signaling* and *Routing* classes are connected to the *BSC* class. The *Signaling* class is responsible for generating and processing signaling messages. The *Routing* class generates and processes routing protocols information, and selects which bundles should be exchanged, based on the routing protocol under use. The *BAD* class interacts with the *BufferManagement* class that is responsible for applying a drop policy when buffer congestion occurs and with the *Scheduling* class that applies a scheduling policy to sort the bundles to be sent at a contact opportunity. The *BAD* class also is connected with the *Classification* class that implements the functions for traffic differentiation and with the *De/Aggregation* class that is responsible for generating data bundles with the aggregation of IP packets (according to a bundle assembly algorithm) at the source node, and for de-aggregating them at the destination node.

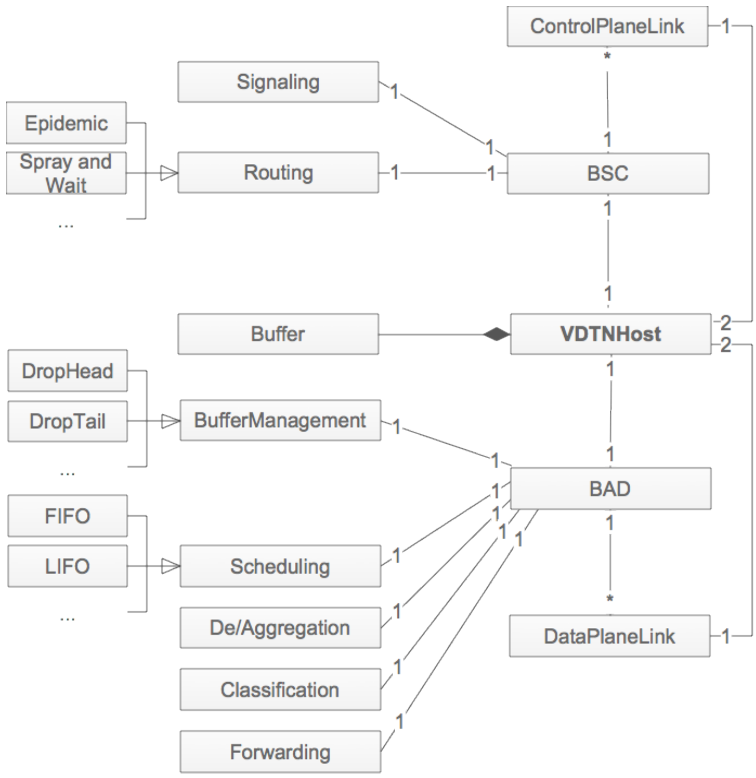

Figure 4.9: UML class diagram of VDTNsim describing the general classes of the VDTN architecture model and the relations among them.

Further details about the interaction between the control plane and the data plane are provided in Figure 4.10. This figure depicts a UML activity diagram that describes the overall flow of control, from activity to activity, executed at each plane. Each network node autonomously manages its control plane and data plane link connections. Nodes are always searching for new contact opportunities using their control plane link connection (with low-power, low bandwidth, and long-range coverage), which is always active. A high-level decision module is responsible for analyzing and processing the control information exchanged at a new contact opportunity, as discussed in Section 3.3. This module decides whether the contact should be ignored or accepted, and may determine the amount of time that it lasts. If the decision module accepts the contact opportunity, then the control information is used for the data plane setup, activation, control, and deactivation, in order to optimize the data bundle transmission, performed at the data plane. Nodes use their data plane link connection (with high-power, high bandwidth, and short-range coverage) to exchange data bundles.

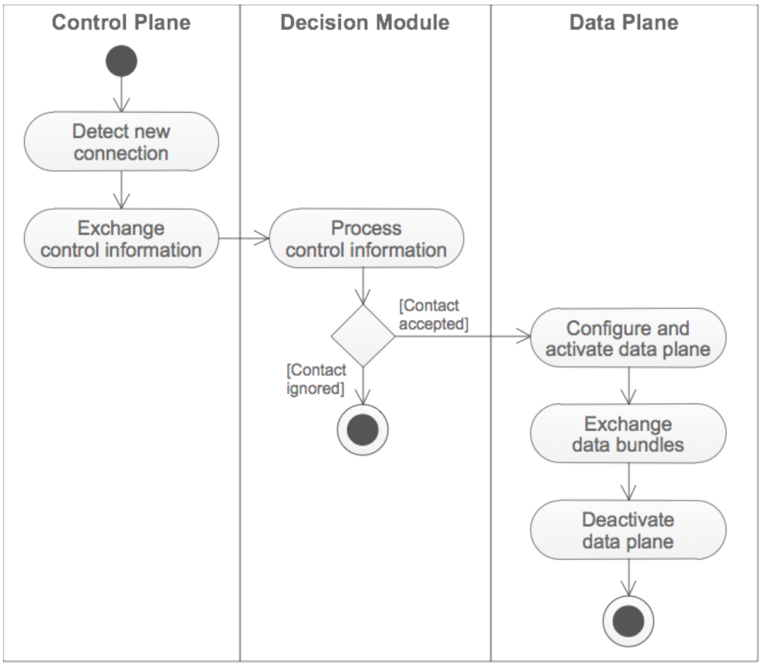

Figure 4.10: UML activity diagram of VDTNsim describing the control and data planes interaction coordinated by the decision module.

Regarding the implementation of VDTNsim simulation tool, one of the major concerns was the programming of all components in a complete modular way, in order to be flexible, easily modified, and extensible. Another concern was the preservation of the simple plain-text simulation configuration files used by the ONE. These files were extended to include support to the parameters required by the protocols, algorithms, and services involved in VDTNs, which were developed in the context of this thesis and that are going to be presented in the next Chapters. Some examples of these extensions are presented in the following figures. Figure 4.11 presents an example of the out-of-band signaling configuration, with the use of two network radio interfaces, each one with different capabilities. Figure 4.12 shows an example of the GeoSpray routing protocol parameters configuration in a simulation scenario. Figure 4.13 shows how to configure a percentage of the nodes' data plane buffer capacity and bandwidth resources to cooperate in bundle relay.

```
# Nodes have the following radio interfaces
# Low speed, long range, interface for control information exchange
Group.signalingInterfaceOn = true
Group.signalingInterfaceTransmitRange = 100
Group.signalingInterfaceTransmitSpeed = 125k
# High speed, short range, interface for data bundles exchange
Group.dataInterfaceTransmitRange = 30
Group.dataInterfaceTransmitSpeed = 562.5k
```

Figure 4.11: Example of configuring radio interfaces for control information and data bundles exchange (out-of-band signaling).

```
Group.router = GeoSprayRouter
GeoSprayRouter.nrofCopies = 15
GeoSprayRouter.binaryMode = true
GeoSprayRouter.clearBufferModuleActive = true
GeoSprayRouter.geographicModuleActive = true
GeoSprayRouter.euclideanDistance = false
GeoSprayRouter.focusModuleActive = true
```

Figure 4.12: Example of configuring GeoSpray routing protocol parameters.

```
# Send Queue Mode
Group.sendQueue = 21
Group.cooperativeSchedulingThreshold = [1.0; 0.9; 0.8; 0.7; 0.6; 0.5]
# Drop Queue Mode
Group.dropQueue = 7
Group.cooperativeBufferThreshold = [1.0; 0.9; 0.8; 0.7; 0.6; 0.5]
```

Figure 4.13: Example of configuring a percentage of data plane buffer capacity and bandwidth resources to cooperate in bundle relay.

Several modules implemented in VDTNsim may be used not only for the simulation of VDTN networks, but also for DTN research. Examples include the GeOpps DTN routing protocol [25] presented in Subsubsection 2.3.2.1, various scheduling and dropping policies, buffer management schemes, and traffic differentiation mechanisms presented in Sections 3.4, 6.4, and 6.5. These modules can be easily implemented in the ONE simulator (the base of VDTNsim simulation tool).

Some of the available simulation report modules were updated to provide other functionalities for VDTNs. Figure 4.14 illustrates an example of a simulation report that was updated to collect statistics about traffic differentiation and to provide additional details about the total traffic volume transferred (in bytes). The performance metrics presented in this report were previously described in Figure 4.7. Figure 4.15 shows an example of another simulation report that was developed to analyze the total number of contacts that were registered per hour for each type of network nodes.

```
Bundle (i.e., message) stats for scenario SNW
sim_time: 43200.0000

Overall Statistics (for all priority classes)
created: 5921 -> 3556.073102 Mbytes
started: 24918 -> 24924.183773 Mbytes
relayed: 21049 -> 20560.713958 Mbytes
aborted: 3867 -> 4360.626200 Mbytes
dropped: 19369 -> 16294.628198 Mbytes
removed: 4278 -> 4446.646491 Mbytes
```

```
delivered: 1997 -> 1965.992030 Mbytes
delivery_prob: 0.3373
response_prob: 0.0000
overhead_ratio: 9.5403
latency_avg: 2025.7191
latency_med: 1754.2000
hopcount_avg: 2.4076
hopcount_med: 2
buffertime_avg: 2300.9217
buffertime_med: 1996.4000
rtt_avg: NaN
rtt_med: NaN

Priority Class: 0 - BULK
created: 1982 -> 346.873177 Mbytes
started: 2006 -> 352.107077 Mbytes
relayed: 1950 -> 341.615943 Mbytes
aborted: 56 -> 10.491134 Mbytes
dropped: 3487 -> 610.729027 Mbytes
removed: 232 -> 40.716688 Mbytes
delivered: 176 -> 30.633577 Mbytes
delivery_prob: 0.0888
response_prob: 0.0000
overhead_ratio: 10.0795
latency_avg: 1567.8307
latency_med: 1095.7000
hopcount_avg: 1.9205
hopcount_med: 2
buffertime_avg: 818.2897
buffertime_med: 282.2000
rtt_avg: NaN
rtt_med: NaN

Priority Class: 1 - NORMAL
created: 1968 -> 984.699993 Mbytes
started: 2385 -> 1215.266950 Mbytes
relayed: 2193 -> 1110.546942 Mbytes
aborted: 192 -> 104.720008 Mbytes
dropped: 3678 -> 1852.022504 Mbytes
removed: 260 -> 130.233236 Mbytes
delivered: 191 -> 96.266178 Mbytes
delivery_prob: 0.0971
response_prob: 0.0000
overhead_ratio: 10.4817
latency_avg: 1756.0801
latency_med: 1199.8000
hopcount_avg: 1.9058
```

```
hopcount_med: 2
buffertime_avg: 926.4037
buffertime_med: 292.6000
rtt_avg: NaN
rtt_med: NaN

Priority Class: 2 - EXPEDITED
created: 1971 -> 2224.499932 Mbytes
started: 20527 -> 23356.809746 Mbytes
relayed: 16906 -> 19108.551073 Mbytes
aborted: 3619 -> 4245.415058 Mbytes
dropped: 12204 -> 13831.876667 Mbytes
removed: 3786 -> 4275.696567 Mbytes
delivered: 1630 -> 1839.092275 Mbytes
delivery_prob: 0.8270
response_prob: 0.0000
overhead_ratio: 9.3718
latency_avg: 2106.7556
latency_med: 1856.1000
hopcount_avg: 2.5190
hopcount_med: 2
buffertime_avg: 2984.2713
buffertime_med: 2955.3000
rtt_avg: NaN
rtt_med: NaN
```

Figure 4.14: Bundle stats report with support for traffic differentiation and showing the volume of bytes transferred over the network.

Hour	RelayNodes	TerminalNodes	MobileNodes	AllNodes
0	152	0	1163	1315
1	157	0	1179	1336
2	158	0	1087	1245
3	156	0	1231	1387
4	150	0	1183	1333
5	184	0	1124	1308
6	137	0	1217	1354
7	146	0	1177	1323
8	162	0	1262	1424
9	180	0	1243	1423
10	145	0	1222	1367
11	146	0	1146	1292

Figure 4.15: Total number of contacts registered per hour for each type of network nodes.

4.2.3. Map-based Model Representation of the *Serra da Estrela* Region

In addition to the development of VDTNsim, it was created a map-based model to simulate VDTN scenarios, considering a rural dispersed region. It was considered the map from the *Serra da Estrela* (Portugal), which is a mountain region that covers an area with large dimensions (approximately 2500 Km^2), shown in Figure 4.16.

The real-world map-based model of this region was created using Google™ Maps [254] and the OpenJUMP geographic information system (GIS) [255], as shown in Figure 4.17. Figure 4.18 presents VDTNsim running a simulation scenario with this map-based model.

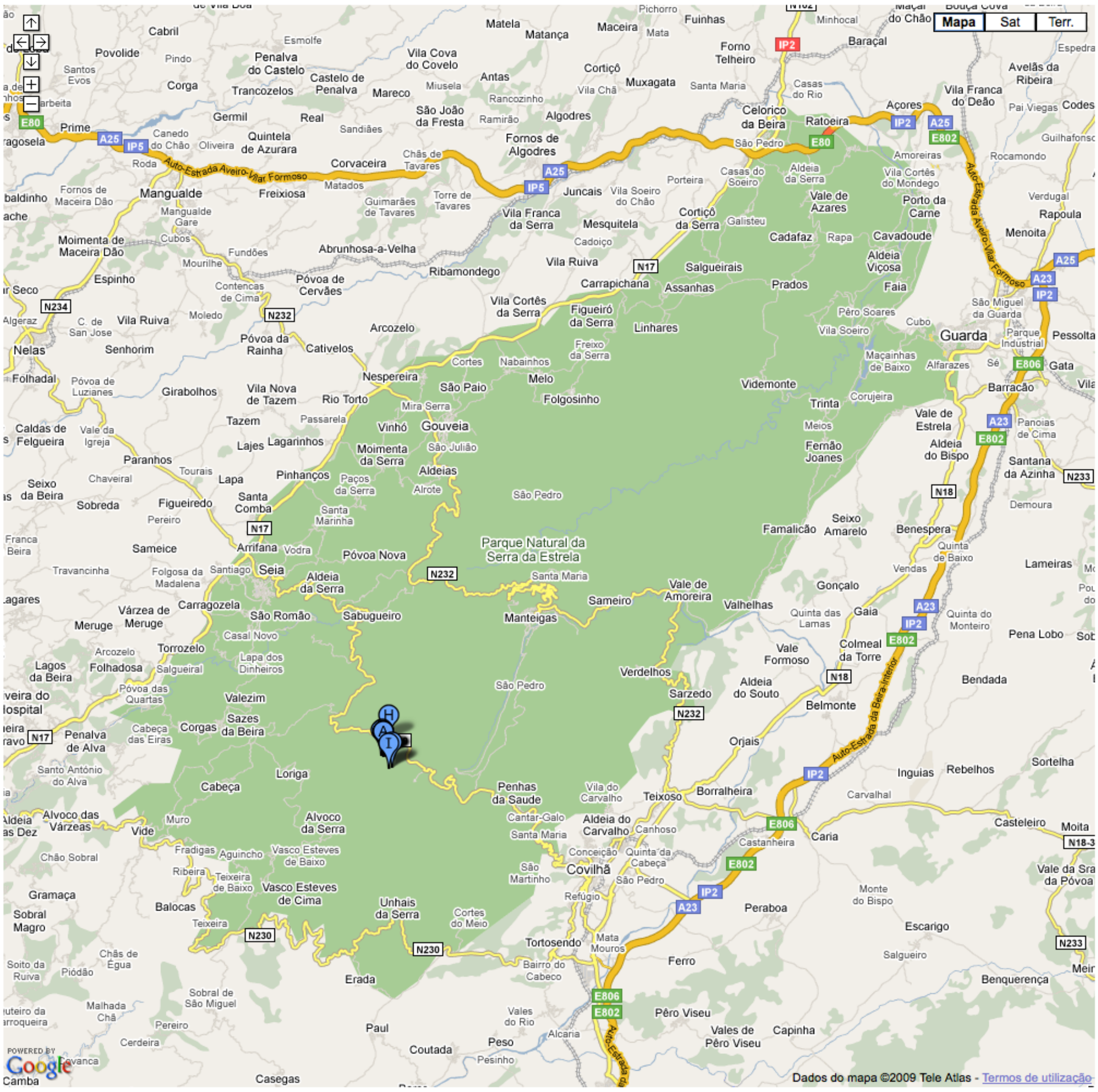

Figure 4.16: Google™ Map of the *Serra da Estrela* region, Portugal.

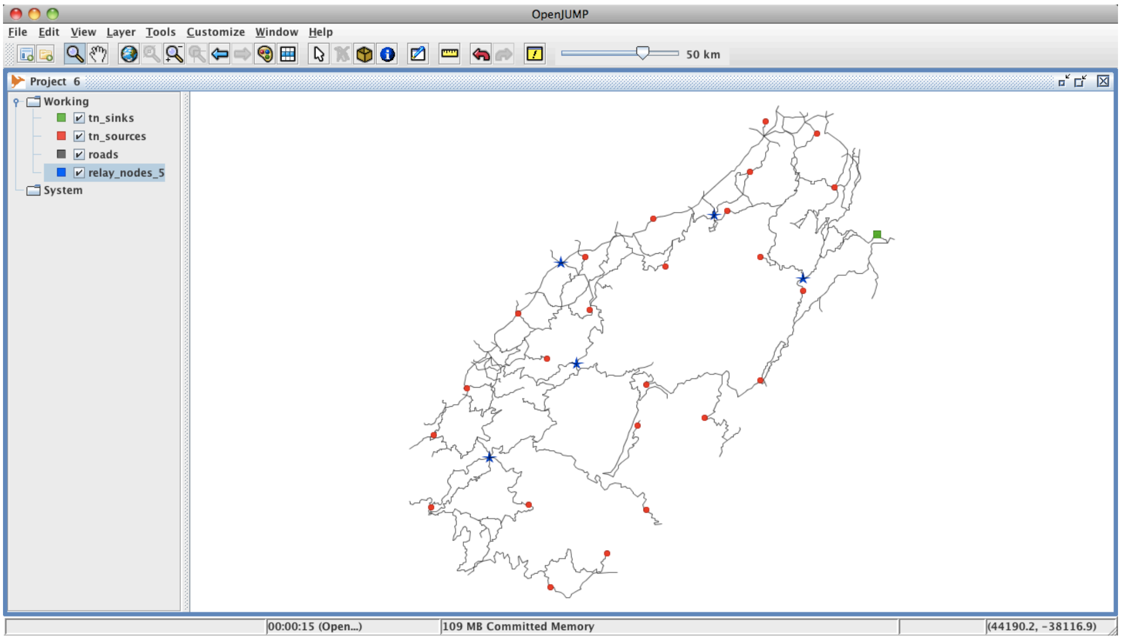

Figure 4.17: Using OpenJUMP to develop a map-based model of the *Serra da Estrela* region, Portugal.

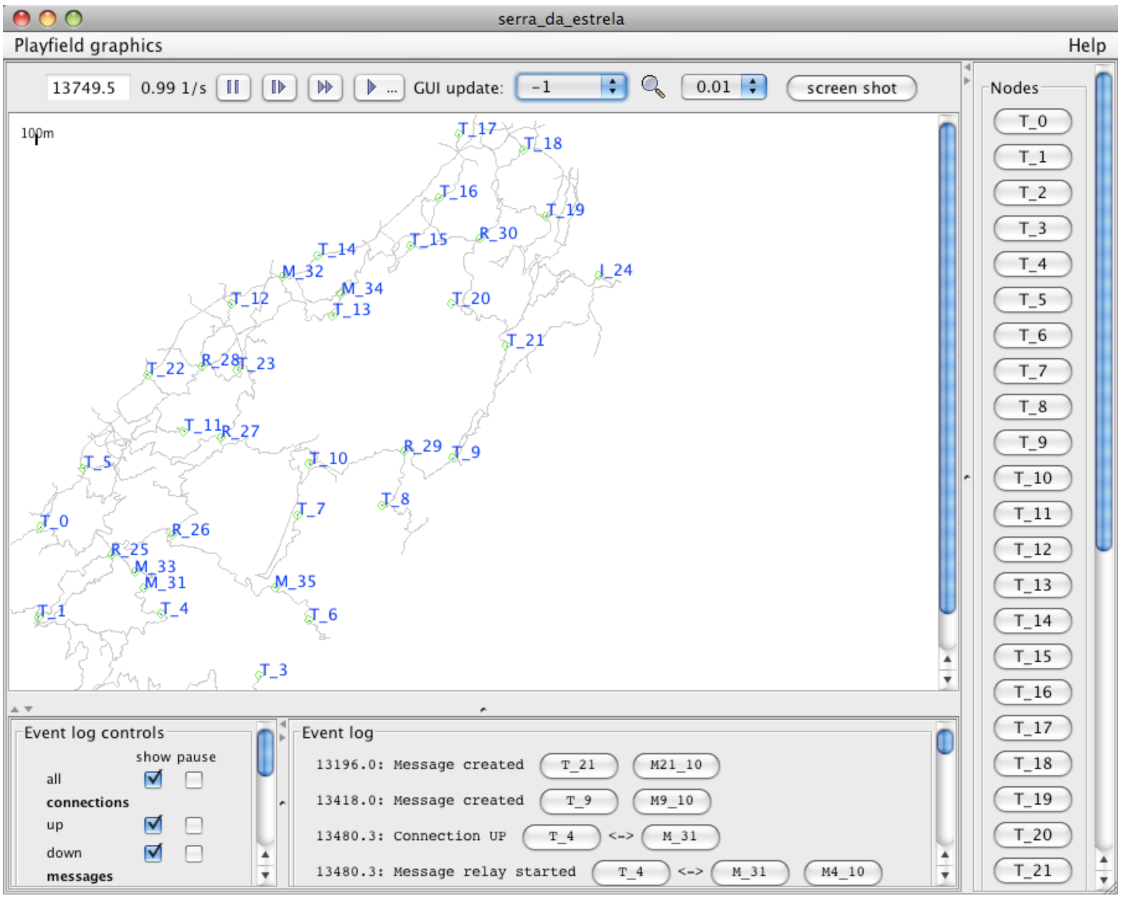

Figure 4.18: VDTNsim running a rural connectivity scenario in the *Serra da Estrela* region, Portugal.

4.3. Design and Implementation of a Laboratory Testbed

Although a simulator is helpful during the development, performance evaluation, and validation of new protocols, algorithms, services, and applications, it is important to implement, evaluate, and demonstrate them in a testbed, in order to assess their performance under more realistic conditions. Several real-world testbeds have been presented in the literature related with vehicular communications. The majority of them are developed for a particular topic of research, ranging from physical layer aspects to experimentation of applications. Some examples of these testbeds are described here.

VanLAN [256, 257] is a testbed composed of eleven basestations and two vehicles, which was developed to investigate the characteristics of WiFi-based connectivity in urban settings. It was used to evaluate how the raw connectivity varies as the vehicle moves and whether it is stable across traversals of the same location.

In [258], the authors were interested to evaluate the possibility of exploring open Wi-Fi networks in urban and suburban areas to allow data uploads from cars to Internet servers. A measurement study was conducted over a vehicular testbed. Nine distinct cars collected data about open access points deployed in and around the Boston (USA) metropolitan area, during a period of 290 hours of driving.

A large-scale VANET testbed running over 4000 taxis in Shanghai (China) is presented in [259]. The information about GPS data collected from the taxis was used to construct a realistic, large-scale mobility model, which was named Shanghai urban vehicular network (SUVnet).

Cabernet [113] is a system developed for improving open WiFi data delivery to moving vehicles based on two components: QuickWiFi for improving connection establishment time, and Cabernet Transport Protocol (CTP) for enhancing throughput over opportunistic WiFi networks. This system was evaluated under real-world conditions on a 10-taxi testbed in the Boston (USA) area.

In [260], a real vehicular ad hoc testbed composed by two vehicles and an access point was used to test the feasibility of a peer-to-peer file sharing application named CarTorrent. Another example of a VANET testbed composed of two cars is presented in [261]. The main objective of this testbed was to conduct experimental measurements of vehicle-to-vehicle communication, in order to study the critical factors that affect the quality of video transmission over a VANET in different scenarios.

DemonstRator for Intelligent Vehicular Environments (DRIVE) [262] is a modular, flexible, reconfigurable testbed demonstrator that allows studying network-layer aspects of vehicular communications (e.g., intra-vehicular, inter-vehicular, and vehicle to infrastructure communication), and advanced services for vehicular users.

UMass DieselNet [205, 263], Fleet testbed [264], and Drive-Thru [99, 265] are examples of real-world testbeds that were developed for supporting research and development of delay-tolerant networking techniques in vehicular communications.

The UMass DieselNet [205, 263] is a bus-based DTN testbed deployed on 40 buses operated by the UMass Amherst (USA). This testbed has been used to study routing protocols for DTN networks, mobility models of bus-to-bus connectivity, and to investigate the use of throwboxes (i.e., stationary relay nodes) to increase contact opportunities and troughput.

Fleet testbed [264] is composed of 27 cars, each one equipped with a CarTel [111, 112] embedded platform that interfaces with a variety of sensors in a car, processes the collected data, and delivers it to an Internet server, providing services to users. CarTel uses wireless networks opportunistically, and shields applications from the underlying details and network disruptions.

The Drive-thru Internet project [99, 265] investigated the problematic of providing Internet access to mobile users in moving vehicles (cars, trains, etc.), based on WLAN hot spots deployed along the roads, in rest areas, or at gas stations. The project proposed an architecture that allows applications to deal with intermittent connectivity and evaluated the communication characteristics when UDP or TCP standard transport protocols were used.

Deploying and operating a real-world testbed to increase knowledge about vehicular communications and to evaluate the behavior/performance of protocols, algorithms, services, and applications under a large-scale network supposes a great effort and has a high associated cost. Moreover, such a testbed has limited flexibility and its use is limited to those who have access to it. These insights motivated the proposal, design, and creation of a versatile laboratory testbed for VDTN networks, called VDTN@Lab. This testbed was developed at the NetGNA research group [58] in the framework of the *Project VDTN@Lab* - an internal project of the *Instituto de Telecomunicações* [266] and in the framework of the *Specific Joint Research Project VDTN* of the Euro-NF Network of Excellence of the Seventh Framework Programme of EU [39, 267].

VDTN@Lab testbed provides *i)* the emulation of VDTNs allowing live experiments with prototyped hardware and software embedded into robots, computers, netbooks, and portable digital assistants (PDAs); *ii)* an integrated environment capable to emulate VDTN protocol stacks, algorithms, services, and applications; *iii)* operation under emulated realistic operating conditions; and *iv)* recreation of a variety of application scenarios. This prototype is described in the next Subsection.

4.3.1. VDTN@Lab Prototype

The VDTN@Lab testbed design follows the general UML modeling guidelines above presented for the VDTNsim simulation tool. The design is modular with well-defined interfaces between the hardware and software components. This enables updating different hardware/software components with minimal impacts on the others. Another important aspect is that interested researchers can easily reproduce this testbed, as the hardware necessary to perform it is not expensive, it is easily available and easy to set up, and the software is hardware device independent as much as possible. Furthermore, the software has been developed in such a way as to adapt itself to a future deployment in a real-world testbed with minimum efforts.

The testbed used in the studies presented in this work considers three types of network nodes, previously described in Section 3.2 and shown in Figure 4.19 (terminal nodes, mobile nodes, and stationary relay nodes). Desktop and laptop computers are used to emulate the terminal nodes and the relay nodes. Mobile nodes are emulated using LEGO MINDSTORMS NXT robots [268] with integrated PDAs or netbooks.

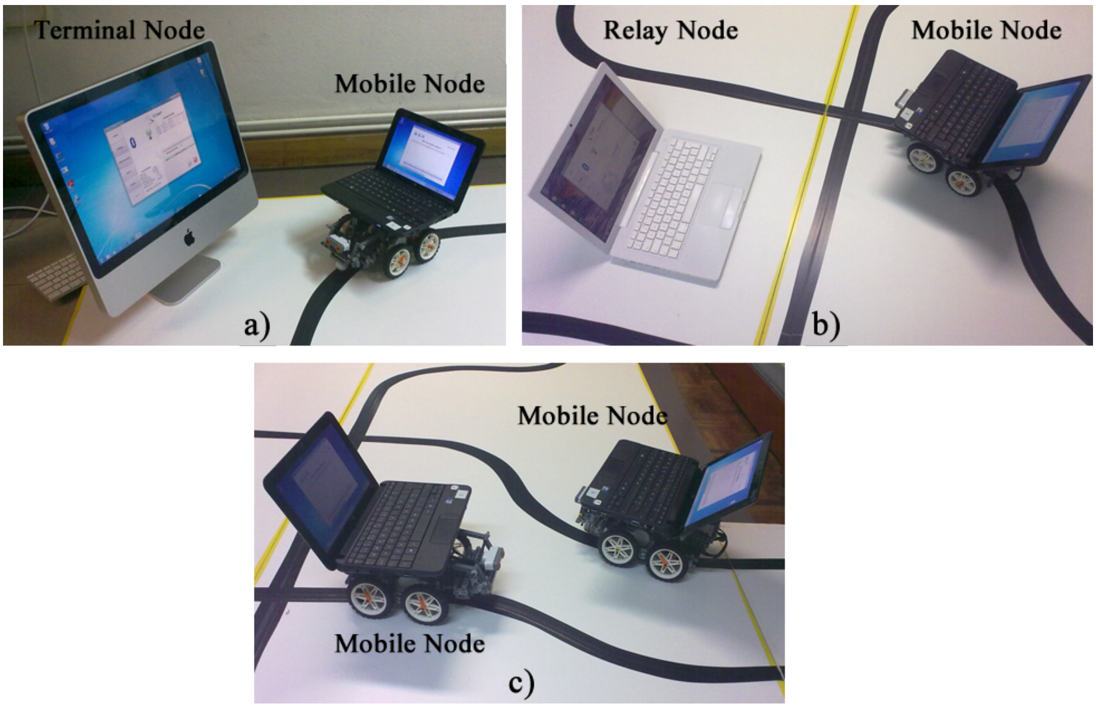

Figure 4.19: Network nodes in the VDTN@Lab testbed.

LEGO MINDSTORMS is a LEGO set designed to build and program small robots. It includes: *i)* LEGO TECHNIC building elements like gears, wheels, tracks, and tires; *ii)* one NXT intelligent micro-computer brick that acts as the brain of the robot and thus can be programmed to read sensor input and activate the servo motors; *iii)* two touch sensors able to detect if the robot hit an object; *iv)* one ultrasonic sensor that makes the robot "see" and detect motion; *v)* one colour sensor that can distinguish between colours, detect light settings and also work like a lamp; *vi)* three interactive servo motors with built-in rotation sensors; and *vii)* connector cables for linking motors and sensors to the NXT.

LEGO NXT robots have interesting technical specifications such as a 32-bit ARM7 microcontroller, 256 KB (kilobytes) Flash, 64 KB RAM, and Bluetooth wireless communication. Nevertheless, these specifications are considered insufficient to emulate the tasks performed by mobile nodes in VDTN networks. To solve this problem, it was necessary to develop a NXT robot that can move as a vehicle and has the ability of carrying a PDA or a netbook, where VDTN protocol stacks, algorithms, services, and applications are deployed. Figure 4.20 shows the NXT robot constructed as a basic vehicle. The robot uses 2 motors to drive the front wheels and has an ultrasonic sensor on the front to detect obstacles.

The use of PDA devices was considered in a preliminary prototype of the testbed (Figure 4.20 *(a)*). However, the programming API for the mobile platform (.Net Compact Framework [269]) did not provide all the functionality required. In addition, a variety of problems related with the use and management of the PDAs' built-in network interfaces (WiFi and Bluetooth) motivated the PDAs replacement by netbooks (Figure 4.20 *(b)*).

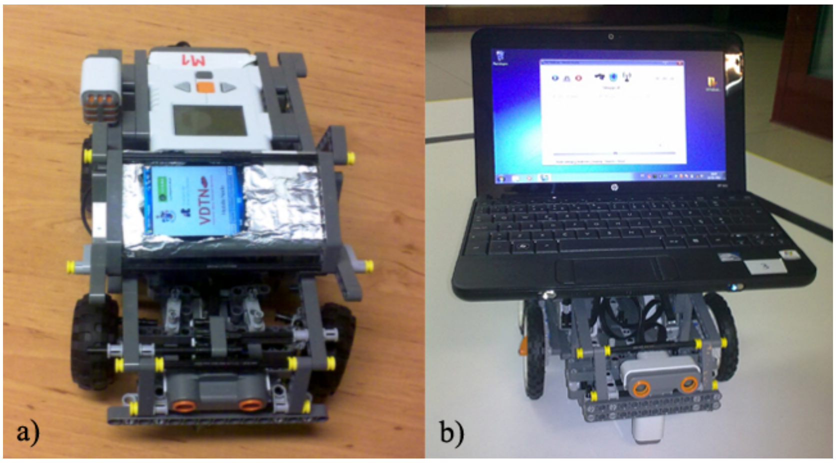

Figure 4.20: A photo of a mobile node created using a LEGO MINDSTORMS NXT robot with an integrated *(a)* PDA or *(b)* netbook.

NXT-G is an icon-based drag-and-drop programming software that comes bundled with the NXT robots. This software was used to program the robotic cars with several mobility models, which emulate the vehicles movement (e.g., random movement along roads or route-based movement). This allows evaluating the effects of different mobility models on the performance of VDTN architecture and related protocols, algorithms, services, and applications. The NXT-G graphical environment is presented in Figure 4.21.

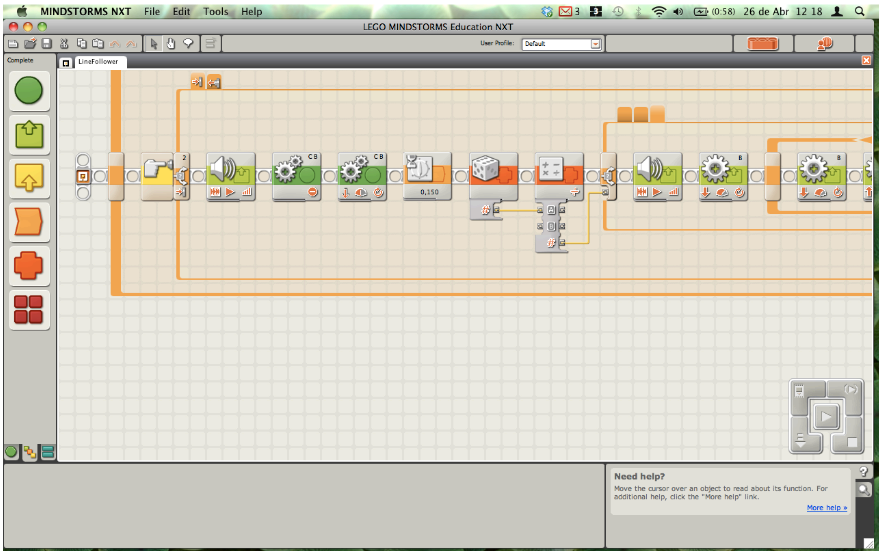

Figure 4.21: Screenshot of NXT-G showing the program blocks that implement a mobility model.

The testbed nodes are equipped with IEEE 802.11 b/g (WiFi) and Bluetooth wireless networking capabilities. These technologies are used to implement the out-of-band signaling feature with the separation between control and data planes. Bluetooth is used to exchange control information, whereas IEEE 802.11 b/g is used for transmission of data bundles. Figure 4.19 shows some interactions between mobile nodes, terminal nodes, and relay nodes.

Software modules were developed to implement the VDTN architecture principles above presented in Section 3.2, as well as several DTN routing protocols (e.g., Direct Delivery, First Contact, Epidemic, Binary and Source Spray and Wait, and PRoPHET) above described in Subsection 2.3.2, and scheduling and dropping policies (e.g., FIFO, LIFO, random selection, remaining lifetime, and replicated copies) that will be presented in Section 6.5. They also provide functionalities to emulate network resource constraints (e.g., buffer size, connection speed rate, and connection range), to emulate different operation conditions (e.g., cooperative behavior), and to emulate network applications with different traffic characteristics and different "quality of service" requirements. In addition, the software modules provide management tools and advanced statistics reports. For example, it is possible to collect statistical data about the delivery ratio, the average delivery delay, the dropping ratio, the number of contacts per time unit (e.g., hour), the average contact time and the historic of nodes that have stored-carried-and-forwarded each of the delivered bundles.

The software modules were programmed in C# [270] using the .Net Compact Framework [269] version 3.5 for running in the PDA's Windows Mobile 6.1, and using the .NET Framework for running in the desktops, netbooks, and laptops with Windows 7 operating system. The graphical user interface of the software running on the mobile nodes, terminal nodes, and stationary relay nodes is presented, respectively, in Figure 4.22, Figure 4.23, and Figure 4.24.

Figure 4.25 shows the graphical user interface that can be used to configure the testbed settings.

a) b)

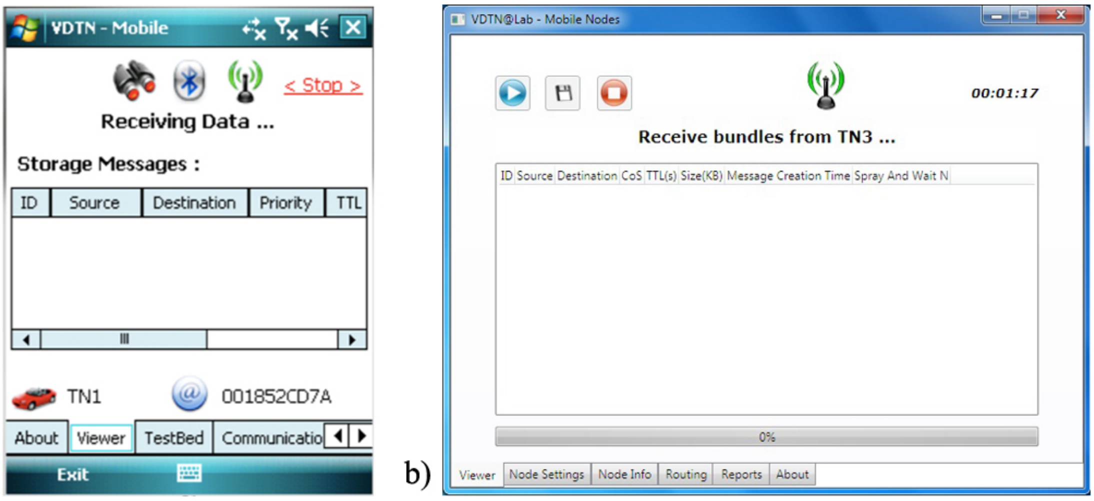

Figure 4.22: VDTN@Lab software user interface for mobile nodes (*(a)* PDAs; *(b)* netbooks).

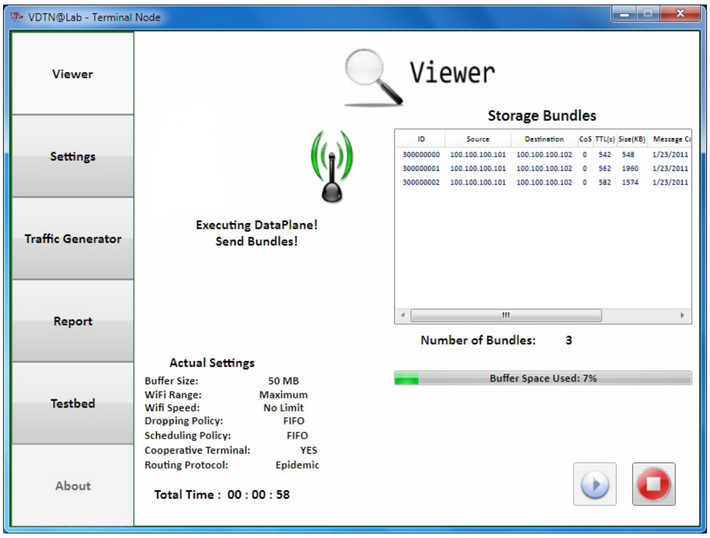

Figure 4.23: VDTN@Lab software user interface for terminal nodes.

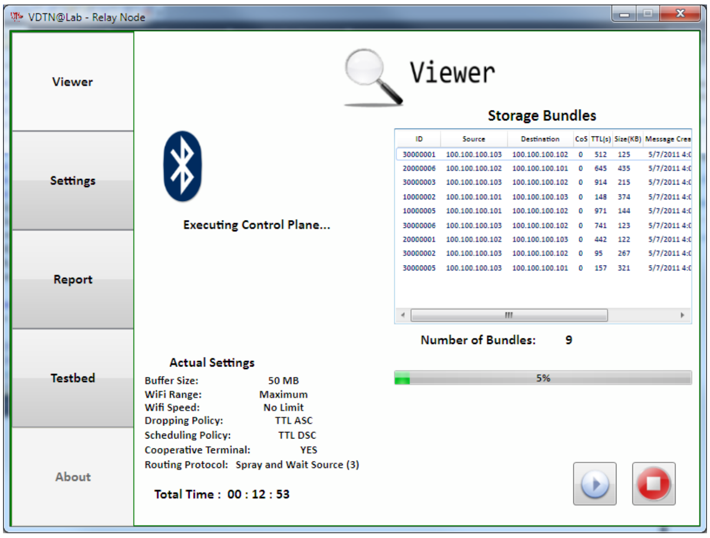

Figure 4.24: VDTN@Lab software user interface for relay nodes.

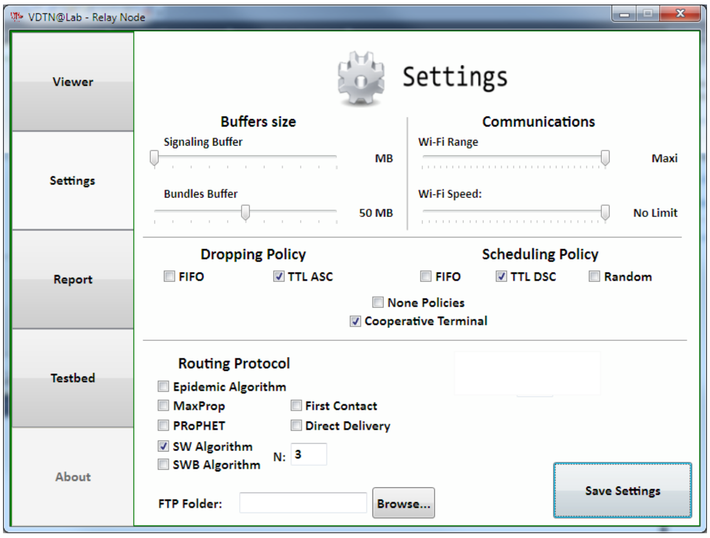

Figure 4.25: VDTN@Lab software user interface for configuring testbed settings.

Figure 4.26 and Figure 4.27 show VDTN@Lab testbed running experiments on two different scenarios. The first scenario, presented in Figure 4.26, was set up to demonstrate and evaluate the use of a VDTN in a rural region. In this scenario, mobile nodes were configured to follow different pre-defined paths, thus emulating bus routes. In the second scenario, shown in Figure 4.27, mobile nodes follow a random movement along the road topology in the sense that any road can be selected when a mobile node arrives at a crossroads/intersection.

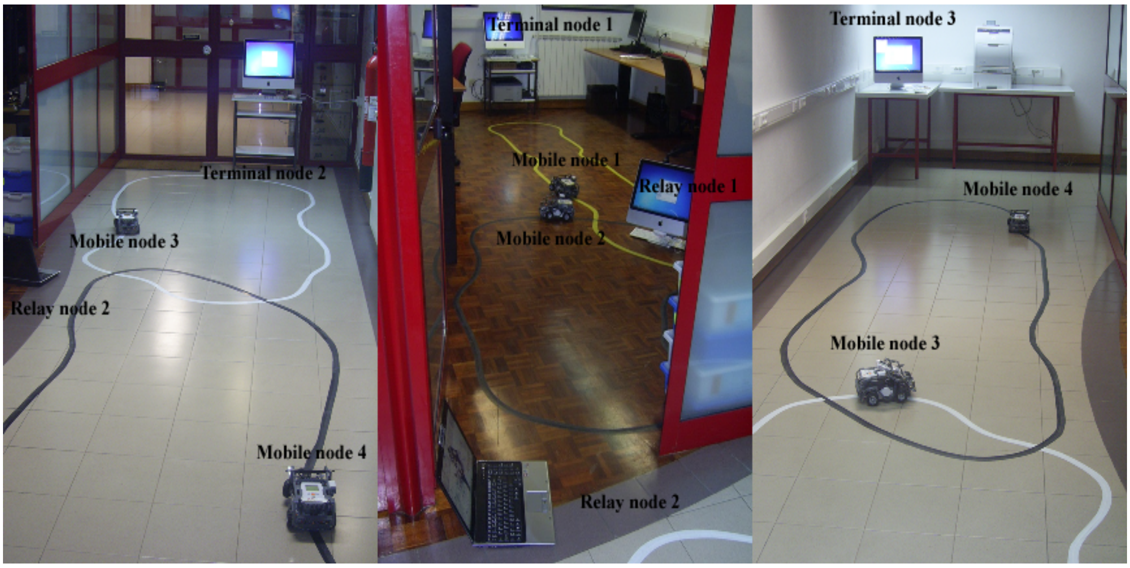

Figure 4.26: Photos of the VDTN@Lab testbed running experiments on a rural connectivity scenario with a route-based movement model.

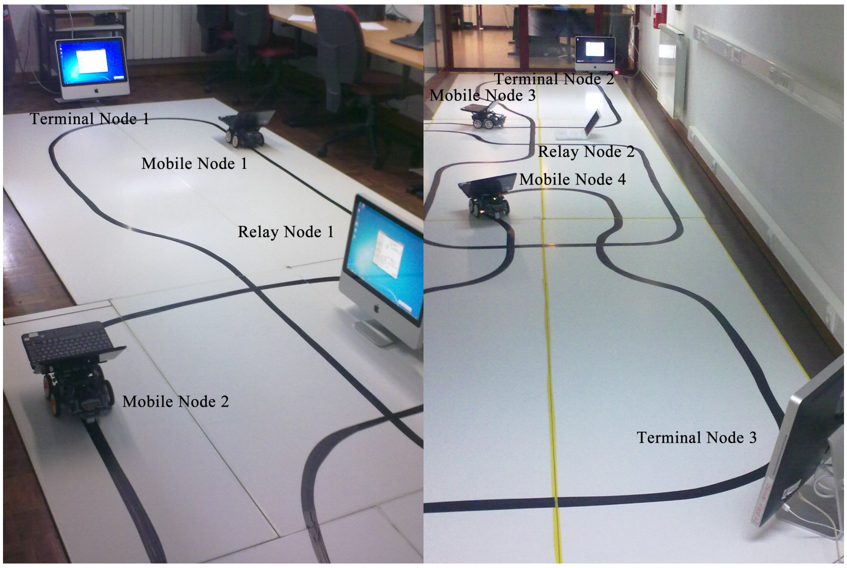

Figure 4.27: Photos of the VDTN@Lab testbed running experiments with a random movement model along the road topology.

4.4. Summary

In this Chapter, the objectives, design, and implementation of a simulator and a laboratory testbed for vehicular delay-tolerant networks were presented. The proposal of VDTN architecture presented in Chapter 3 led to the necessity of developing a simulation tool, which models the characteristics of this network architecture. After having analyzed available simulators for vehicular ad hoc networks and delay-tolerant networks, it was decided to develop a simulation tool for VDTNs based on the well-known the ONE simulator [250, 252].

This simulation tool, called VDTNsim, was presented in Section 4.2. VDTNsim allows the development, experimentation, and performance evaluation of new protocols, algorithms and services for VDTNs. Therefore, it is used as a simulation tool to support the studies of performance assessment presented in the next Chapters. It is worth to notice that since VDTNsim is an extension of the ONE simulator, it does not only bring new modules to the ONE developer community, but also contributes to a wider adoption of this simulator. A map-based model of the *Serra da Estrela* region, Portugal, which was created to allow the simulation of rural connectivity scenarios in VDTNsim, was also presented.

Section 4.3 started with an overview of some of the testbeds available in the literature for research studies in vehicular communications. The motivation and goals for developing a laboratory testbed for VDTN networks were also described. Then, a VDTN prototype, called VDTN@Lab, was presented. VDTN@Lab features an emulation capability, allowing live experiments with prototyped hardware and software embedded into robots, computers, netbooks, and portable digital assistants. It was designed and developed to demonstrate the interaction in an emulated environment as well as for validation of simulation models. The VDTN@Lab testbed has been used to perform series of experiments reported in the last Chapter of this work.

Both the VDTNsim simulation tool (including the map-based model of the *Serra da Estrela* region) and the software running on the VDTN@Lab testbed will be available soon for the research community.

Chapter 5

Performance Assessment of VDTNs in Rural Connectivity Scenarios

5.1. Introduction

In spite of its astonishing growth around the globe in the last two decades, the Internet is still far from becoming universal. There are still vast numbers of areas in the world, which have no Internet access. In the majority of these areas, high cost and/or environmental conditions prohibit construction of any durable infrastructure and effective traditional wireless networks to provide Internet access. For many communities utilizing technologies, such as, very small aperture terminal (VSAT), microwave dishes and WiMax antennas is simply not feasible. For example, monthly fees for VSAT in Africa can be as high as $5000 per month per Mbit/s [271]. WiMax technology, typically, requires high equipment cost, expertise, and considerable planning. Microwave dishes require line-of-sight and hence, become very susceptible to obstacles such as buildings or trees, and its performance can easily be affected under various environmental conditions like high humidity.

Lack of universal broadband connectivity continues to create serious gaps between poor and rich communities. Studies have shown that by connecting to the digital world, underprivileged communities can benefit from economic prosperity, social stability, and the personal and professional development of their members [272]. These studies emphasize that the information communities technologies (ICTs) can bring the digital technologies to the isolated and marginalized communities and help ensure their integration into wider society at the local, national, and international levels.

In the past few years, a growing number of projects have been focusing on bringing connectivity to unreachable and disconnected rural communities in an inexpensive manner. Some examples of these projects are described briefly below.

The DakNet project [94] aimed to provide low-cost Internet connectivity to rural villages in India. In this project, mobile access points (MAPs) are mounted on vehicles and when they are in contact with kiosks located at villages data is exchanged between them. Afterwards, MAPs can use an access point to download/upload information from/to the Internet.

The Saami Network Connectivity (SNC) project [95] focuses on providing Internet connectivity to the Saami population of the reindeer herders, who live in Lapland and move from their villages through the year, following the migration of reindeers. The Wizzy Digital Courier service [93] was designed to provide Internet access to schools located in remote villages of South Africa. This system is based on a courier using a motorbike, equipped with a USB storage device, which travels from a village school to a large city with broadband Internet access.

The Message Ferry project [168] aimed to develop a data delivery system in disconnected areas. In this system, mobile nodes called message ferries (e.g., cars, buses, boats, etc), move around the network and collect messages from source nodes. The Networking for Communications Challenged Communities (N4C) [92] is another example of a recent project that aims to create an opportunistic networking architecture to allow Internet access on the remote, vast and sparsely populated Swedish Lapland, and on Kocevje region of the Slovenian mountain.

Similar to these projects based on DTN concepts, vehicular delay-tolerant networks can create a communication infrastructure composed of vehicular nodes and fixed nodes to provide low cost non-real time data exchange (e.g., e-mail, Web access, telemedicine, environmental monitoring, and other data collection applications) on a rural remote region sparsely populated, without a network infrastructure. Figure 5.1 illustrates such a scenario. Three VDTN node types are considered, terminal nodes, mobile nodes, and relay nodes. Terminal nodes (traffic sources) are located in isolated regions (villages) and provide network connection to end-users. At least one of the terminal nodes may have Internet access (traffic sink). Mobile nodes (i.e., vehicles) are opportunistically exploited to carry data between the traffic sources and the traffic sink. They can move along the roads “randomly” (e.g., cars) or follow predefined routes (e.g., buses). Due to the large distances involved in such scenario and low node density, network nodes are rarely in communication range with one another, which results in few transmission opportunities and high and unpredictable delays. Therefore, to increase the number and frequency of contact opportunities, stationary relay nodes are deployed at road intersections. As previously explained, these nodes allow passing by mobile nodes to collect and deposit data on them.

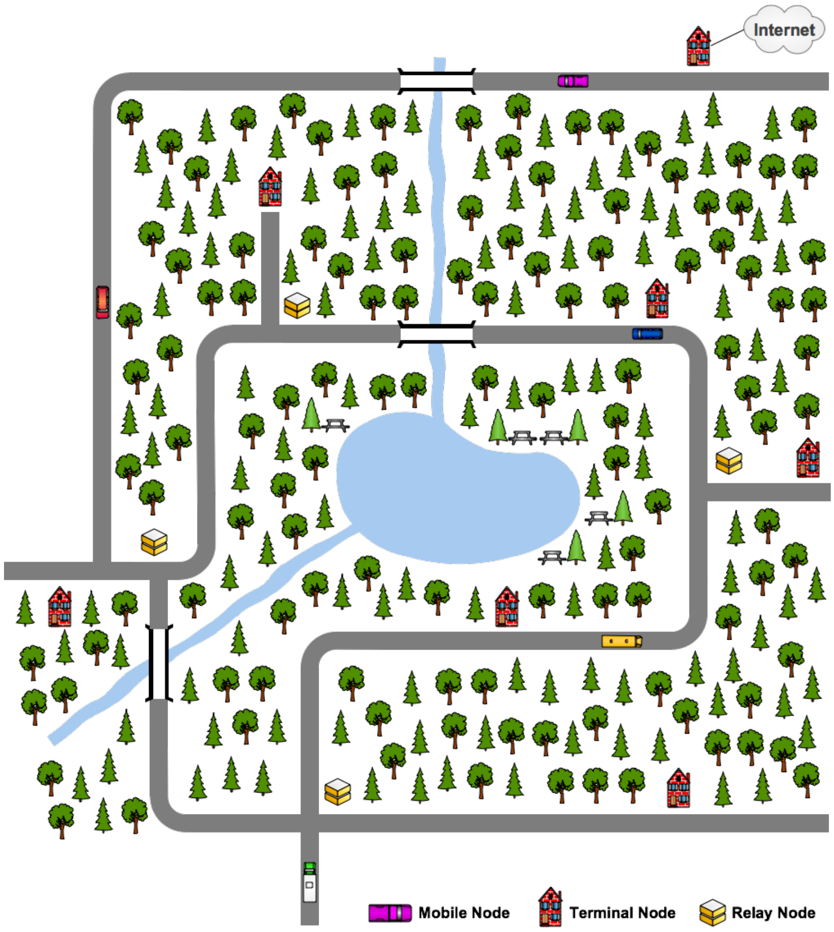

Figure 5.1: Example of a vehicular delay-tolerant network deployment in a rural scenario.

This Chapter addresses some of the issues arising from the study of the VDTNs applicability to enable asynchronous (i.e., non-real time) applications (e.g., e-mail, Web access, telemedicine, environmental monitoring, and data collection applications), on remote villages in underdeveloped countries or rural areas, disconnected from technology. The remainder of this Chapter is organized as follows. Section 5.2 presents the performance metrics considered in the simulation studies reported in this Chapter, which were conducted using the VDTNsim simulation tool described in Section 4.2. Section 5.3 evaluates the importance of stationary relay nodes to improve the number of contact opportunities, and thus the network performance in terms of the bundle delivery probability and the bundle average delivery delay. Section 5.4 studies the influence of the mobile nodes density and the mobile nodes movement models on the number of observed contact opportunities, and their effect on the performance of the network taking into account the bundle delivery probability and the bundle average delivery delay. Section 5.5 addresses the study of the potential problems caused by storage constraints in the bundle delivery probability. Finally, main conclusions are presented in Section 5.6.

For each simulation setup considered in these studies, thirty simulation runs with different random seeds were performed, thus giving statistically reliable results (applying central limit theorem [273]). Only the mean values of the simulation runs are represented in the plots, since the standard deviations were negligible.

Part of this Chapter was published in [45-49].

5.2. Performance Metrics

This Section describes the following three performance metrics used to evaluate the network performance: number of contacts per hour, bundle delivery probability, and bundle average delivery delay.

Number of contacts per hour: It is defined as the number of contacts registered per hour between all network nodes. It is assumed that two nodes are in contact when the distance between them is shorter than the transmission range.

Bundle delivery probability: It is defined as the ratio between the total number of unique bundles (i.e., does not count bundle replicas) that have reached the destination node(s) and the total number of unique bundles that were originated (i.e., created) at the source node(s). It is calculated according to Equation 5.1, where *DP* is the bundle delivery probability, *Db* is the total number of unique delivered bundles, and *Cb* is the total number of unique created bundles.

$$DP = \frac{Db}{Cb} \tag{5.1}$$

Bundle average delivery delay: It is defined as the average time between bundles creation and delivery. It is calculated according to Equation 5.2, where $\overline{DD}$ is the bundle average delivery delay, Td_i is the time when the bunde *i* was delivered, Tc_i is the time when the bunde *i* was created, and *Db* is the total number of unique delivered bundles.

$$\overline{DD} = \frac{\sum_{i=1}^{Db}(Td_i - Tc_i)}{Db} \tag{5.2}$$

5.3. Impact of Stationary Relay Nodes on the Network Performance

In extremely sparse scenarios with low node density, like rural and remote regions, the store-carry-and-forward paradigm used in VDTNs can be insufficient, by itself, to accomplish data delivery. As discussed in Subsection 2.3.3, this problem can be addressed by the use of stationary relay nodes that can be installed on road intersections to increase the number and frequency of contact opportunities between mobile nodes.

This Section studies the impact of stationary relay nodes on increasing the number of contact opportunities and their effect on the overall network performance in terms of bundle delivery probability and bundle average delivery delay.

5.3.1. Network Scenario

The simulation scenario considers a map-based model representation of the *Serra da Estrela Region*, a Portuguese Mountain Region that covers an area with approximately 2500 Km^2, shown in Figure 5.2. It is considered a simulation period of 12 hours (e.g., from 8:00 to 20:00), in a fully cooperative opportunistic environment without knowledge of the traffic matrix and contact opportunities.

Twenty-four real-world village locations, represented in the same figure, were selected to place the terminal nodes that act as traffic sources. Each traffic source node has a 2 GB (gigabytes) buffer, and generates bundles using an inter-bundle creation interval in range [15, 30] minutes with uniformly distributed random values. Each bundle has a size in range [500 KB, 2 MB] 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 12 vehicles (e.g., mobile nodes) moves along the map roads and each has a 2 GB buffer. When a vehicle reaches a terminal node, it randomly waits from 30 to 60 minutes. Then, it selects its next destination node in accordance to a probability, assuming a 90% probability to select a random traffic source as its next destination and a 10% probability to select the traffic sink. Afterwards, a random speed between 30 and 80 km/h is selected, and the vehicle moves along the roads using the shortest available path.

This study evaluates the impact of using 0, 5, or 10 stationary relay nodes, each one with a 2 GB buffer, deployed in the predefined map locations shown in Figure 5.2. Network nodes connect to each other using IEEE 802.11b with a data rate of 6 Mbps [274], and a transmission range of 350 meters using omni-directional antennas.

The impact of stationary relay nodes is examined on the performance (bundle delivery probability and bundle average delivery delay) of the widely applicable above-described multiple-copy DTN-based routing strategies: Epidemic [200], MaxProp [24], PRoPHET [203], and Spray and Wait [202].

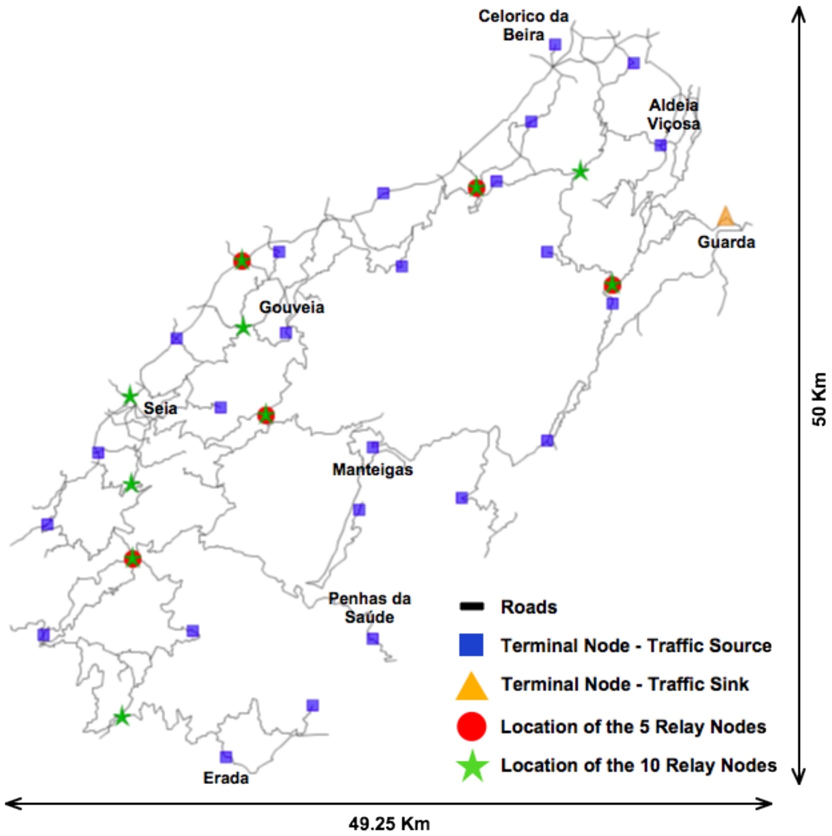

Figure 5.2: Illustration of the *Serra da Estrela* region with the location of the terminal nodes and the stationary relay nodes.

5.3.2. Performance Assessment

The large dimension of this scenario, the low network node density, and the above-described vehicle's mobility model, lead to a small number of contacts registered per hour. Deploying stationary relay nodes in this scenario is a complex task, since it was assumed that no information is available about the transmission opportunities and traffic matrix. A non-uniform strategy [208] was used to select the locations of the relay nodes, positioning them preferentially in the core of the network. As may be seen in Figure 5.3, this simple strategy produces significantly positive results even in this sparse scenario, increasing the number of contact opportunities between the network nodes.

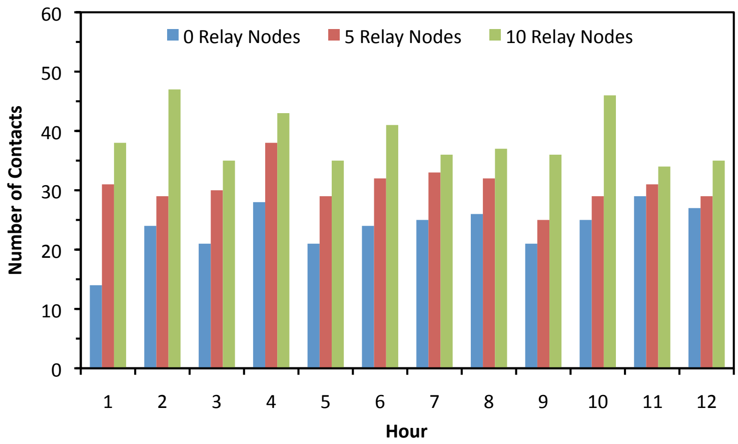

Figure 5.3: Number of contacts per hour between all network nodes as function of the number of stationary relay nodes.

Figure 5.4 shows the bundle delivery probability for each considered routing protocol, assuming 0, 5, or 10 stationary relay nodes. As may be seen in this figure, when no stationary relay nodes are deployed in the network, MaxProp performs better than the other protocols in terms of the bundle delivery probability. It may be observed that deploying 5 stationary relay nodes provides up to 9% of gain in the bundle delivery probability for Epidemic routing protocol, 8% for MaxProp, 7% for Spray and Wait binary variant (with 36 bundle copies), and 1% for Spray and Wait normal variant (with the same number of bundle copies).

Taking into account the dispersed area of this scenario, increasing the number of stationary relay nodes to 10 has a greater effect on the bundle delivery probability of routing protocols. In fact, it can be observed that Epidemic and MaxProp increase their bundle delivery probability in more 5% and 10%, respectively, and PRoPHET improves 27%. The same is observed with Spray and Wait variants that improve 9% and 10%, respectively.

In this scenario, the large buffers of the nodes attenuate Epidemic poor utilization of the network resources. PRoPHET’s “probabilistic routing” approach registers the lowest delivery probabilities irrespective of the number of used relay nodes. Finally, it can also be concluded that MaxProp performs better than the other protocols, and that Spray and Wait binary variant is more effective that the normal variant.

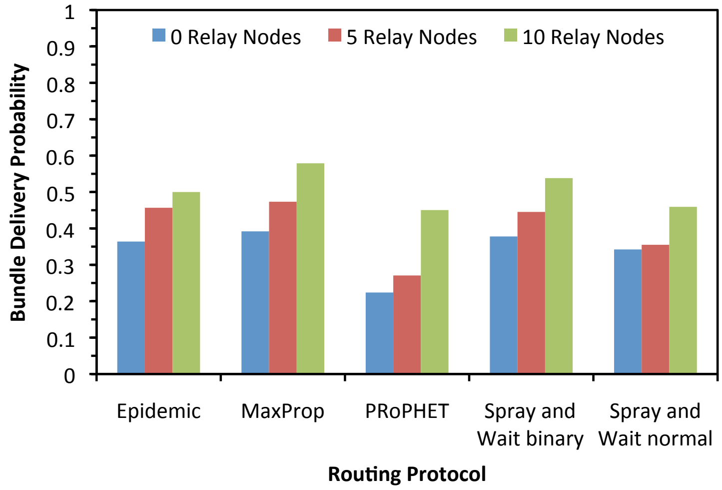

Figure 5.4: Bundle delivery probability as function of the number of stationary relay nodes for Epidemic, Spray and Wait, PRoPHET, and MaxProp routing protocols.

As may be observed in Figure 5.4, PRoPHET not only presents the lowest delivery probabilities, but also the worst performance in respect to the bundle average delivery delay that is shown in Figure 5.5. The remaining routing protocols register similar results for this performance metric across all simulations. The small increase on the bundle average delivery delay when the stationary relay nodes are introduced is related to the time that bundles spend in their buffers, waiting for a vehicle to pick and deliver them to the traffic sink.

Based on results presented in Figure 5.4 and Figure 5.5, it may also be concluded that by deploying stationary relay nodes, more bundles are successfully delivered to the traffic sink without significant time increased to deliver them. The large delivery delays registered in this scenario are due to the vast geographical area.

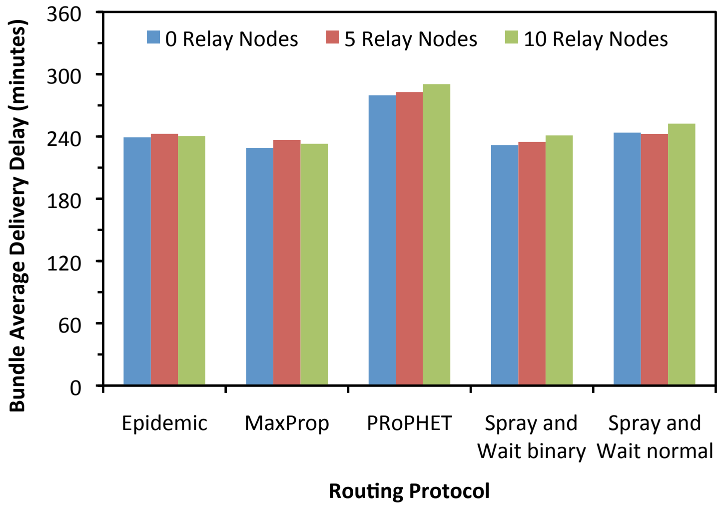

Figure 5.5: Bundle average delivery delay as function of the number of stationary relay nodes for Epidemic, Spray and Wait, PRoPHET, and MaxProp routing protocols.

5.4. Effect of Mobile Node Density and Movement Models on the Network Performance

This Section studies the effect of mobile nodes density and their mobility pattern on the bundle delivery probability and the bundle average delivery delay for VDTNs in rural connectivity scenarios. A simulation-based study is performed considering three different scenarios. Each scenario assumes the changing of the mobile nodes density and considers different groups of mobile nodes moving in accordance to one of three movement models. The first movement model assumes that mobile nodes move between random map locations. In the second movement model, mobile nodes move between the locations of the terminal nodes that represent the traffic sources and the terminal node that represents the traffic sink. Probabilities are associated to these two groups of terminal nodes and are used to determine the mobility pattern of mobile nodes. The third movement model is the map route movement where mobile nodes follow predefined routes moving from terminal node to terminal node (e.g., moving as buses).

5.4.1. Network Settings

To simulate a rural connectivity scenario, the real-world map-based model representation of the *Serra da Estrela* region is considered. This map is shown in Figure 5.6. Twenty-four real-world village locations were selected to place the terminal nodes that act as traffic sources. Each terminal node (traffic source) has a 125 MB (megabytes) buffer, and generates bundles using an inter-bundle creation interval in the range [15, 30] minutes of uniformly distributed random values. Each bundle has a size in the range [500 KB, 2 MB] of uniformly distributed random values. It is assumed that all the bundles exchanged in the simulations have an infinite time to live (TTL). Bundles destination address is the terminal node connected to the Internet that acts as the traffic sink, whose location is also presented in Figure 5.6.

Six relay nodes, each with a 500 MB buffer, are placed at the selected crossroads presented in Figure 5.6. Depending on the simulated scenario, two types of mobile nodes can move along the map roads, cars and buses. Cars have a 125 MB buffer whereas buses have a 250 MB buffer. All the network nodes connect to each other using the standard IEEE 802.11b with a data rate of 6 Mbps [274], and a transmission range of 350 meters using omni-directional antennas.

When mobile nodes are in contact with the traffic sink node, they try to deliver the bundles stored in their buffers. Each bundle successfully delivered is removed from the mobile node buffer, thus freeing storage space. The creation and bundles exchanging is simulated for a period of 12 hours (e.g., from 8:00 to 20:00). It is assumed that the traffic matrix is not provided in advance and there is not any knowledge about the transfer opportunities.

The performance of the above-described (Subsection 2.3.2) four DTN routing protocols, Epidemic [200], MaxProp [24], PRoPHET [203], and Spray and Wait [202], is evaluated for each of the scenarios considered. In addition, PRoPHET and Spray and Wait protocol parameters are changed across the simulations in order to study their influence on the network performance. More specifically, in the case of PRoPHET, the effect of the transitive property (*beta*) is assessed. This parameter is related to the importance given to the information about destinations received from encountered nodes. The value of *beta* is changed between 0, 0.25, and 0.5 (0.25 is the recommended value in [203]). In the case of Spray and Wait, both the normal and binary variants are considered, and the number of bundle copies is varied between 6, 12, and 18. The performance metrics considered in these studies are the bundle delivery probability and the bundle average delivery delay.

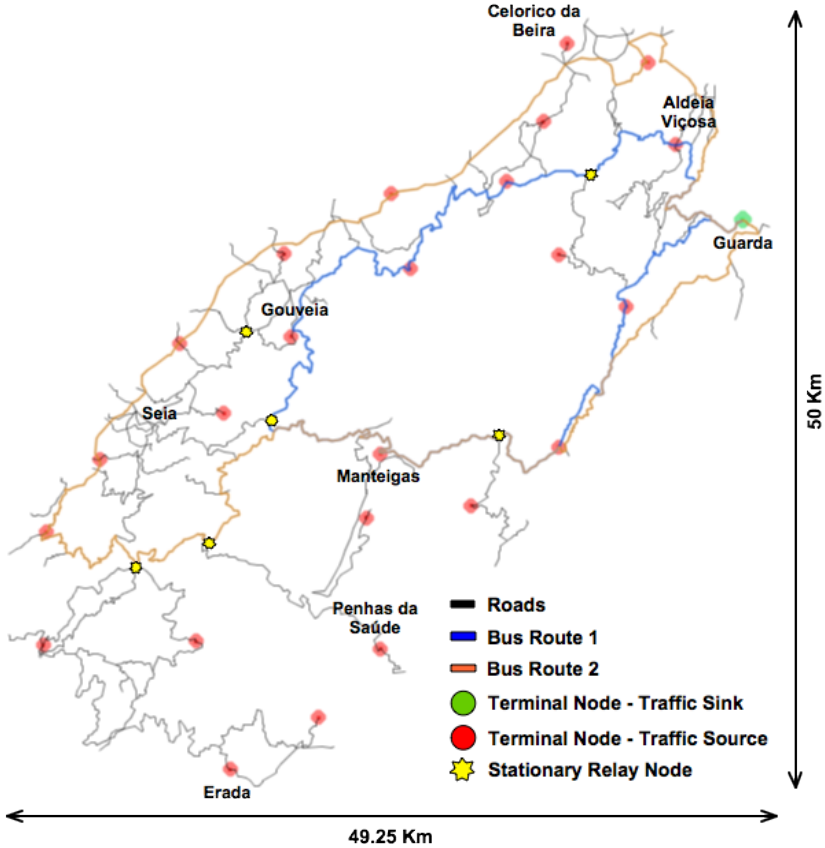

Figure 5.6: Illustration of the *Serra da Estrela* region with the location of the terminal nodes and stationary relay nodes, and the two buses routes.

5.4.2. Performance Results

Scenario 1

The first simulation scenario considers a group of cars moving on roads between random map locations. Once a car reaches a destination, it randomly waits 15 to 30 minutes. Then, it selects a new random location on the map, and a random speed between 30 and 80 km/h.

The car moves to the new destination using the shortest path (road) available. This process is repeated till the end of the simulation time. The performance of the routing protocols is evaluated when 5 or 8 cars follow this movement model.

Figure 5.7 shows that no bundles were successfully delivered in the case where only 5 cars were considered. These results seem surprising at first, but it is important to remember that cars were moving between random map locations. The terminal node that acts as a traffic sink is located in a remote map position, which decreases the probability for cars passing there. They will only pass on that location if the road segment where the traffic sink is located is used in the shortest path to a previous calculated destination. Even if they pass nearby the traffic sink, they will only stop there if its exact map location was select as the next destination, which is highly improbable. All this conditions contribute to the very low delivery probabilities registered even in the case where 8 cars were deployed. Intuitively, placing the traffic sink at a central map point should increase the bundle delivery probability.

Figure 5.7 also shows that Epidemic (E) and MaxProp (M) are the routing protocols that perform better in respect to the bundle delivery probability. Spray and Wait binary mode (SWB) registers better values than its normal mode (SW). In SWB, the bundle delivery probability increases when the number of bundle copies augments from 6 (SWB 6) to 12 (SWB 12) and to 18 (SWB 18), and approximates from the values of E and M. SW registers the same bundle delivery probability for the cases with 6 (SW 6), 12 (SW 12), or 18 (SW 18) bundle copies. PRoPHET did not successfully deliver any bundle for any of the variations of the *beta* parameter: 0 (P 0), 0.25 (P 0.25), and 0.5 (P 0.5).

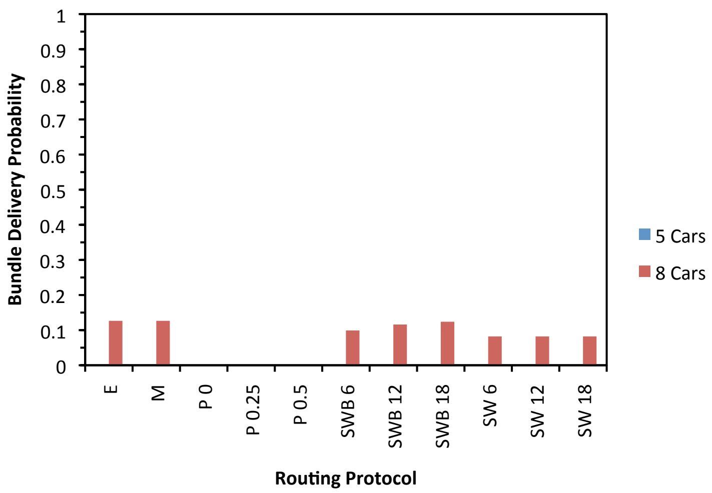

Figure 5.7: Bundle delivery probability for Epidemic, MaxProp, PRoPHET, and Spray and Wait routing protocols with 5 or 8 cars.

In terms of bundle average delivery delay, shown in Figure 5.8, all protocols register similar values. The analysis of Figure 5.9 shows that deploying 8 cars increases the number of contact opportunities, as expected. Therefore, this suggests that more bundles are collected at the terminal nodes and exchanged between cars and relay nodes.

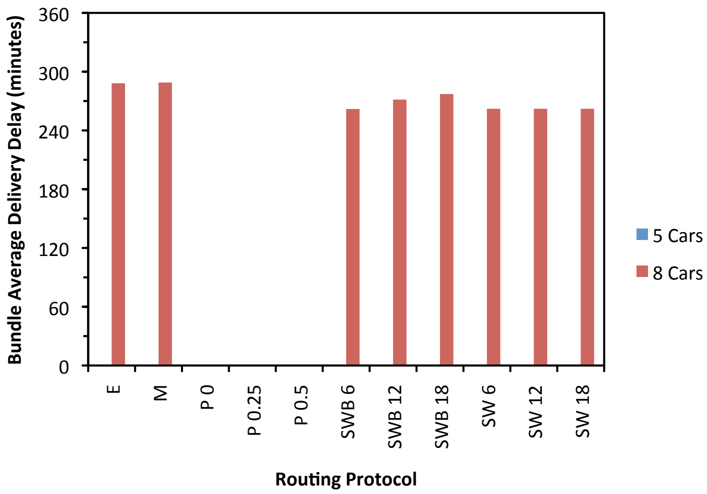

Figure 5.8: Bundle average delivery delay for Epidemic, MaxProp, PRoPHET, and Spray and Wait routing protocols with 5 or 8 cars.

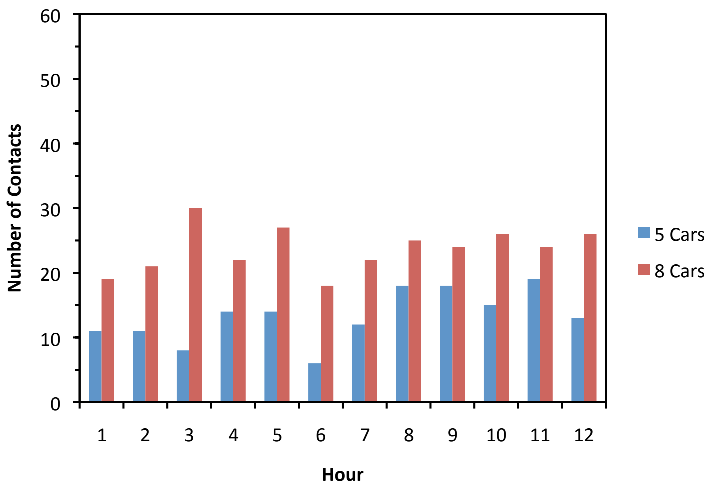

Figure 5.9: Number of contacts per hour between all network nodes with 5 or 8 cars.

Scenario 2

The second scenario considers a group of cars moving along the roads between the terminal nodes. When a car reaches a terminal node, it randomly waits 15 to 30 minutes. Then, instead of selecting any random location for its next destination, the movement model is configured to give a new destination in accordance to a probability calculated as follows. The map data contains two groups of points of interest (PoIs). One of the PoI groups contains the terminal nodes that are the traffic sources and the other contains the terminal node that is the traffic sink. For this scenario, a 15% selection probability is associated to the traffic sink POI group, and 85% selection probability to the traffic sources PoIs group. Hence, there is an 85% probability for the movement model to select a random village (traffic source) as the next destination for the mobile node. After determining the next destination, a random speed between 30 and 80 km/h is selected, and the mobile node moves there using the shortest path. Here, the performance of the routing protocols is evaluated when 5 or 8 cars follow this movement model.

This movement model registers much better delivery probabilities than the ones presented in Scenario 1, as expected. These results are obtained because the cars move only between random traffic sources and the traffic sink. Increasing the number of cars (i.e., the mobile nodes density), the number of contacts per hour also increases (Figure 5.10), which improves the bundle delivery probability, as expected (Figure 5.11).

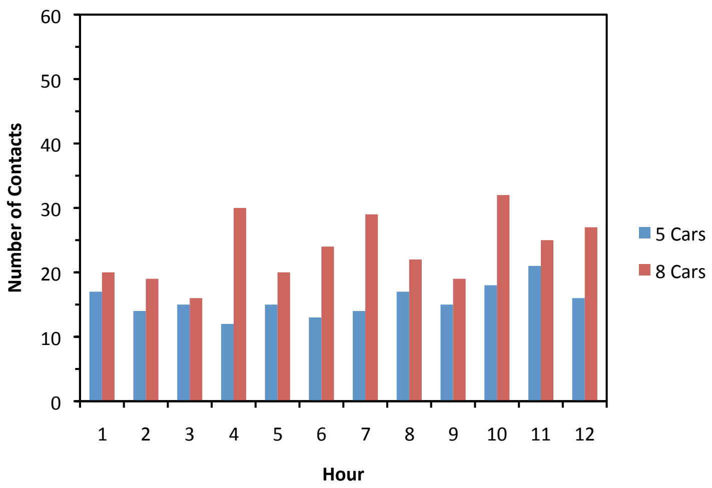

Figure 5.10: Number of contacts per hour between all network nodes with 5 or 8 cars.

Figure 5.11 also shows that, for 5 cars, binary Spray and Wait with 6 copies performs better, followed by the MaxProp protocol. For 8 cars, Spray and Wait protocol also performs better than the other protocols. Its binary variant registers the best delivery probabilities in the cases of 6 and 12 bundle copies. For SWB 18, the bundle delivery probability drops, which suggests that 18 bundle copies lead to a poor utilization of the nodes buffers. The same behavior is observed in its normal variant. Epidemic does not register a big improvement because of its poor utilization of the network resources.

The analysis of PRoPHET behavior confirms the importance of the *beta* parameter. Increasing its value to 0.25 improves the bundle delivery probability. This happens because if *beta* is set to 0 only direct encounters will be used in the calculation of the delivery predictability (used by this routing algorithm). In this type of scenario (dispersed region with a low number of vehicles) the transitive property is very important, since the information about destinations received from encountered nodes should be taken into account.

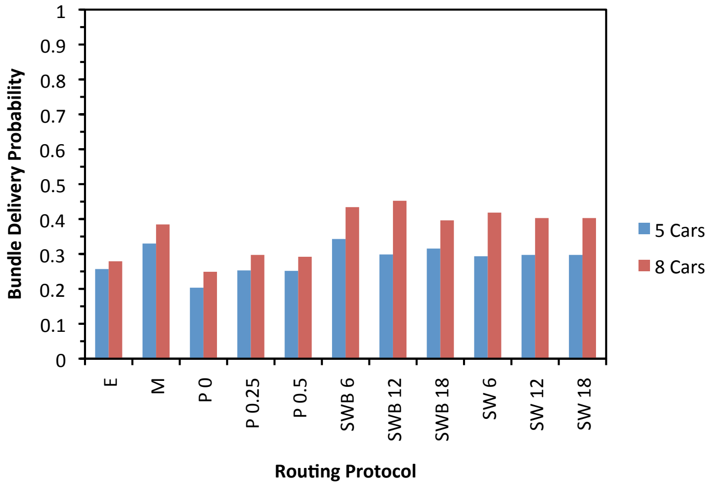

Figure 5.11: Bundle delivery probability for Epidemic, MaxProp, PRoPHET, and Spray and Wait routing protocols with 5 or 8 cars.

Another interesting finding shown in Figure 5.12 is that increasing the number of cars to 8 decreases the bundle average delivery delay in all routing protocols. This is interesting since minimizing the average delivery delay reduces the time that bundles spend in the network, also reducing the contention for resources in the network (e.g., buffer space, bandwidth).

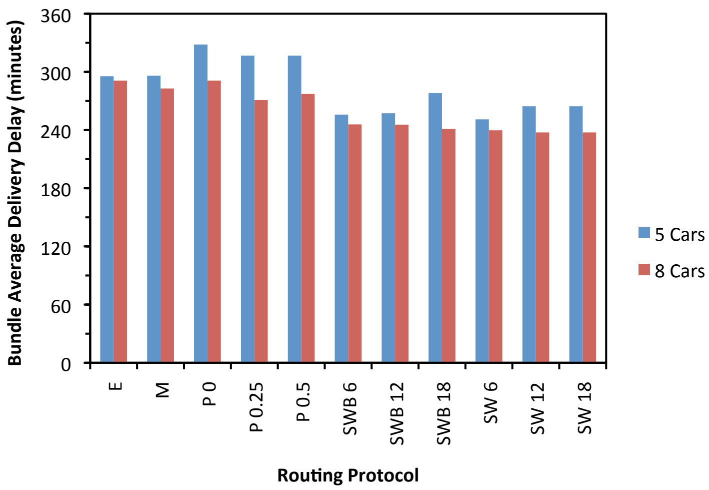

Figure 5.12: Bundle average delivery delay for Epidemic, MaxProp, PRoPHET, and Spray and Wait routing protocols with 5 or 8 cars.

Scenario 3

This last scenario combines the configuration of the other two previous scenarios. Therefore, at the same time, there is a group of 8 cars moving between random map locations, and a group of 8 cars moving in accordance to the movement model based on POI group selection probabilities. Additionally, 1 or 2 buses following the predefined circular routes shown in Figure 5.6 are introduced. Buses move from one terminal node to another. Each time they arrive at a terminal node they stop for a period of 15 minutes, then they select a random speed between 30 and 50 km/h and follow their route to the next terminal node.

The bundle delivery probability increases significantly in this scenario (Figure 5.13) when comparing to the previous ones, as expected. This is mainly due to the buses movement, since they follow predefined circular routes collecting bundles generated on some terminal nodes (traffic sources), and delivering them to the traffic sink. Cars moving randomly over the map also contribute to disseminate data to other cars, buses, and relay nodes. Therefore, they also have an important role to improve the overall network performance. Figure 5.13 shows that when two buses are deployed (instead of one), the bundle delivery probability increases further for all routing protocols. This was expected because the number of contacts per hour increases. The poor utilization of the network resources of the Epidemic protocol is more explicit in this scenario. Therefore, causing it to perform worse than the other routing protocols. When a single bus is used, MaxProp has the best bundle delivery probability compared to the other protocols. When two buses are considered, this protocol only improves the delivery probability slightly.

In this scenario, Spray and Wait binary variant increases the bundle delivery probability when the number of bundle copies is augmented. SWB 18 is the routing protocol variant with the best bundle delivery probability, when 2 buses are deployed. Spray and Wait normal variant decreases the bundle delivery probability when the number of bundle copies is increased. This obervation suggests that, for SW, increasing the number of copies congests nodes buffers. Setting PRoPHET *beta* parameter to 0.25 produces the best results in this scenario.

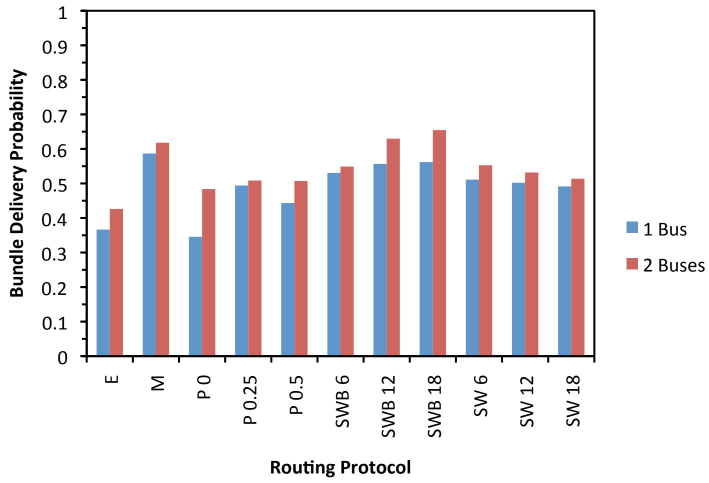

Figure 5.13: Bundle delivery probability for Epidemic, MaxProp, PRoPHET, and Spray and Wait routing protocols with 1 or 2 buses.

Figure 5.14 shows that having 2 buses decreases the bundle average delivery delay in all routing protocols except for SWB 12 and SWB 18. For that specific cases, having 1 or 2 buses results in similar average delivery delays. Even though buses move on circular routes, stopping at predefined places for a certain amount of time, cars did not have access to that information. This would allow scheduling meetings between vehicles and would further increase the overall performance of the VDTN network.

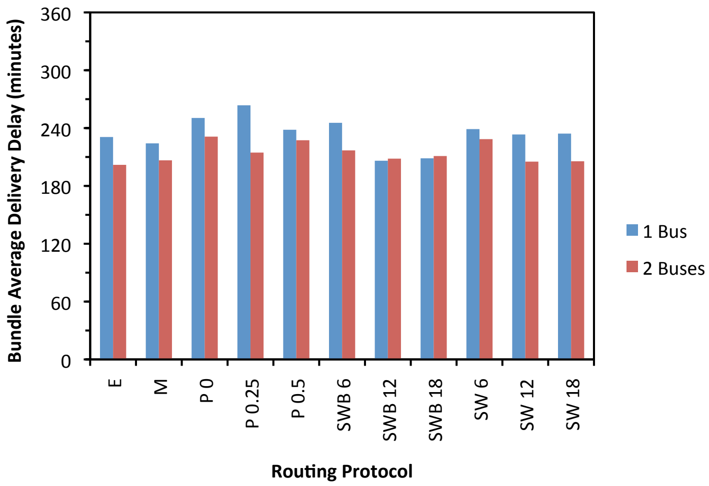

Figure 5.14: Bundle average delivery delay for Epidemic, MaxProp, PRoPHET, and Spray and Wait routing protocols with 1 or 2 buses.

5.5. Impact of Storage Constraints on the Network Performance

This Section analyzes the influence of the nodes' storage capacity on the overall network performance. The impact of varying the buffer size of terminal nodes and mobile nodes on well-known multiple-copy DTN-based routing protocols with distinct replication strategies is studied.

The motivation to introduce different capacities to the buffer size of terminal nodes comes from the fact that besides being traffic sources and traffic sinks, if sufficient storage is available, they can also implement the functionality of relay nodes. Therefore, a terminal node can store data destined for any other terminal node(s), which was leaved there by mobile nodes. This process is illustrated in Figure 5.15. Intuitively, this behavior contributes to improve the bundle delivery probability. In this study, three scenarios are considered, where the number of mobile nodes is increased and, therefore, the number of transmission opportunities is augmented (and the overall network load). The objective is to analyze if increasing the nodes' buffer size has a direct effect on improving the bundle delivery probability.

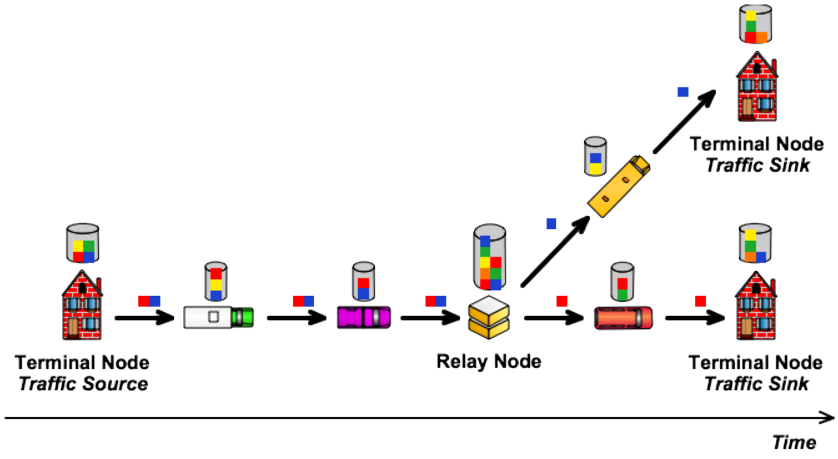

Figure 5.15: Illustration of mobile nodes carrying data between terminal nodes.

5.5.1. Network Setup

This study assumes the use of the real-world map representation of the *Serra da Estrela* region, where 25 real-world sparse village locations are selected to place the terminal nodes (Figure 5.16). It is assumed that each terminal node is simultaneously a traffic source and a traffic sink. Terminal nodes generate bundles using an inter-bundle creation interval in the range [5, 15] minutes of uniformly distributed random values. Each bundle has a size in the range [500 KB, 2 MB] of uniformly distributed random values. All bundles have an infinite time to live. Terminal nodes have a buffer whose size changes between 100, 200, 300, 400 and 500 MB across the simulations, for each scenario.

Six relay nodes, each with a 1 Gbyte buffer, were placed at the crossroads shown in Figure 5.16. The results collected during the simulations guarantee that this amount of storage is large enough and does not bias the results presented below. Mobile nodes move between terminal nodes. When a mobile node reaches a terminal node, it randomly waits 15 to 30 minutes. Then, it selects a new random terminal node as its next destination. Afterwards, a random speed between 30 and 80 km/h is selected and the mobile node moves over there using the shortest available path. Each terminal node has equal probability for being selected. Mobile nodes have a buffer whose size changes between 200 and 400 MB across the simulations, for each scenario.

All network nodes connect to each other using 802.11b with a data rate of 6 Mbps [274], and a transmission range of 350 meters using omni-directional antennas. The creation and bundles exchanging is simulated for a period of 12 hours (e.g., from 8:00 to 20:00). It is assumed that the traffic matrix is not provided in advance and there is not any knowledge about transfer opportunities. Three different scenarios with 6, 12, or 18 mobile nodes moving between terminal nodes are considered. For each scenario the buffer size of the terminal nodes and the mobile nodes is changed, and the performance of the above-described routing protocols Epidemic [200], MaxProp [24], PRoPHET [203], and Spray and Wait [202] is evaluated.

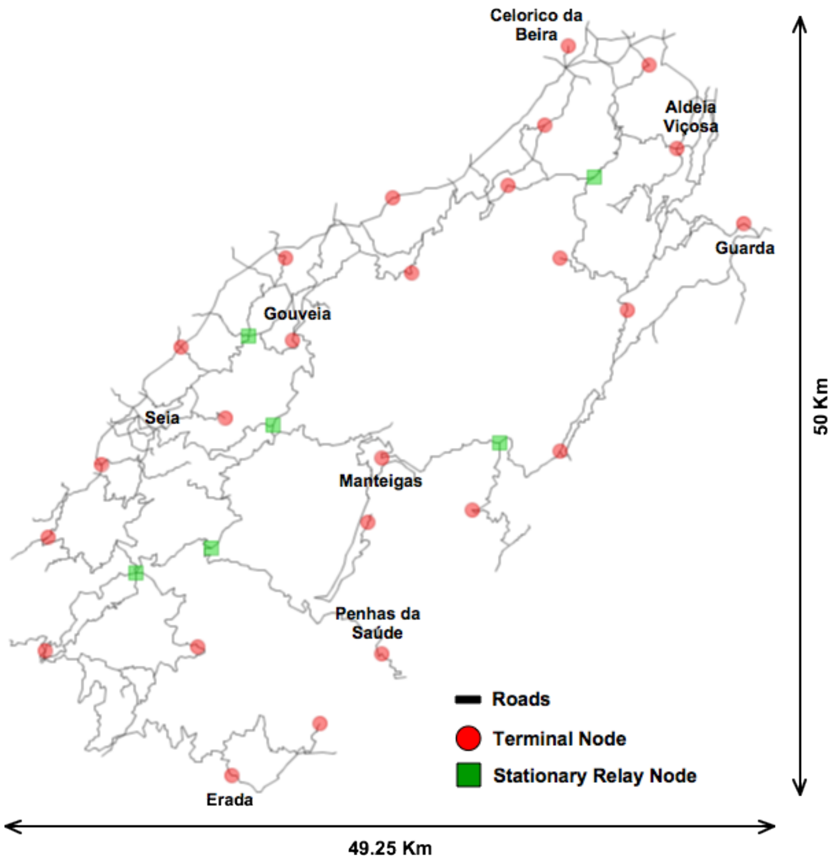

Figure 5.16: Illustration of the *Serra da Estrela* region map area with the location of the terminal nodes and the relay nodes.

5.5.2. Results Analysis

Scenario with 6 Mobile Nodes

First, a scenario where 6 vehicles (i.e., mobile nodes), each with a 200 MB buffer, carry data bundles between terminal nodes is considered. The results collected during simulation shown that 100 MB are enough to store all the bundles created by a terminal node during the 12 simulated hours. This is due to the bundles creation interval and their possible sizes. The terminal nodes' buffer size changes between 100 MB and 500 MB across the simulations.

Figure 5.17 shows the bundle delivery probability for six mobile nodes with 200 MB buffer each one. As may be seen, the Epidemic flooding approach benefits from the increase on the terminal node buffer size, augmenting its bundle delivery probability. This effect is more evident when the buffer size increases from 100 MB to 200 MB. Increasing the buffer size futher only augments the bundle delivery probability slightly. This is caused by the limitation introduced by the number of mobile nodes and their buffer size that restricts the bundles dissemination. MaxProp protocol also floods, but after delivering bundles it explicitly clears them. It performs better than the other protocols when buffers with 400 MB or 500 MB are deployed. PRoPHET registers similar delivery probabilities across the simulations. Spray and Wait binary and normal variants limit the number of copies of each bundle (twelve, in this case). It can be observed that both variants register similar values across the simulations. Moreover, when terminal nodes have buffer sizes smaller than 300 MB, they perform better than the other protocols.

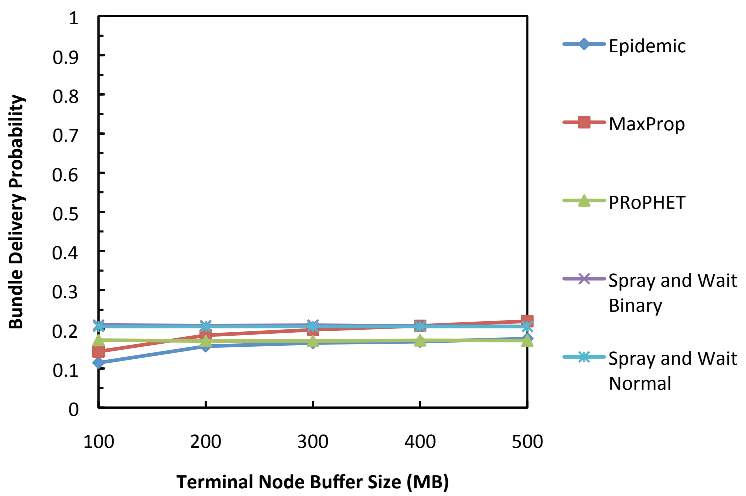

Figure 5.17: Bundle delivery probability as function of terminal nodes buffer size for Epidemic, MaxProp, PRoPHET, Binary and Normal Spray and Wait routing protocols, using 6 mobile nodes with 200 MB buffer size.

Increasing the terminal nodes' buffer size augments the delivery probabilities for Epidemic and MaxProp routing protocols. However, all routing protocols register low delivery probabilities. Since mobile nodes are responsible for physically carrying data, their buffer size was increased to 400 MB, allowing them to store and transport a larger number of bundles. The effect of this modification is shown in Figure 5.18.

As it can be observed, all routing protocols increase their delivery probabilities. Again, as in the previous results, PRoPHET and Spray and Wait present a behavior where no significant effect is registered by changing the terminal nodes' buffer size. In this case, the Spray and Wait binary variant performs better than the other protocols. As expected, increasing the mobile nodes and terminal nodes buffers sizes reduces the effect of Epidemic poor utilization of the network storage resources. Its performance approximates to MaxProp and Spray and Wait.

PRoPHET behavior is caused by its "probabilistic routing" approach. When buffers over 400 MB are deployed it performs worse than the other protocols. Therefore, in this scenario, it does not take any advantage of larger buffers. Finally, comparing Figures 5.17 and 5.18, it is observed that Epidemic and MaxProp register similar results when terminal nodes have 100 MB buffers, independently of the mobile nodes' buffer size. This demonstrates the importance of terminal nodes' storage capacity to increase the bundle delivery probability on these protocols.

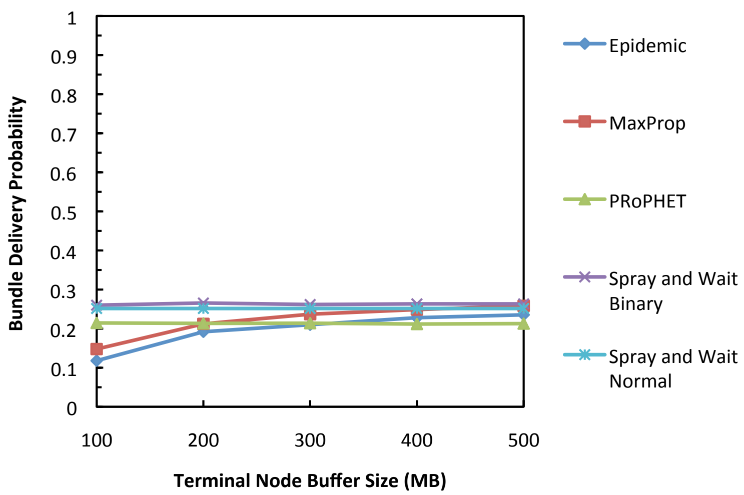

Figure 5.18: Bundle delivery probability as function of terminal nodes buffer size for Epidemic, MaxProp, PRoPHET, Binary and Normal Spray and Wait routing protocols, using 6 mobile nodes with 400 MB buffer size.

Scenario with 12 Mobile Nodes

The second scenario considers the use of 12 mobile nodes instead of 6, each initially with a 200 MB buffer. This increases the number of transmission opportunities and improves the bundle delivery probability, as may be seen in Figure 5.19. As observed in the previous scenario, and because of the same reasons, PRoPHET and Spray and Wait variants register similar values across the simulations, which mean that their performance does not depend on the terminal nodes' buffer size.

Spray and Wait binary variant performs better than the other considered routing protocols. However, with the increase of the buffer size of terminal nodes, the MaxProp performance approximates to Spray and Wait binary. The Epidemic routing protocol poor network resources utilization, caused by its pure flooding scheme, prevents it from increasing the bundle delivery probability when terminal nodes' buffer size is greater than 300 MB.

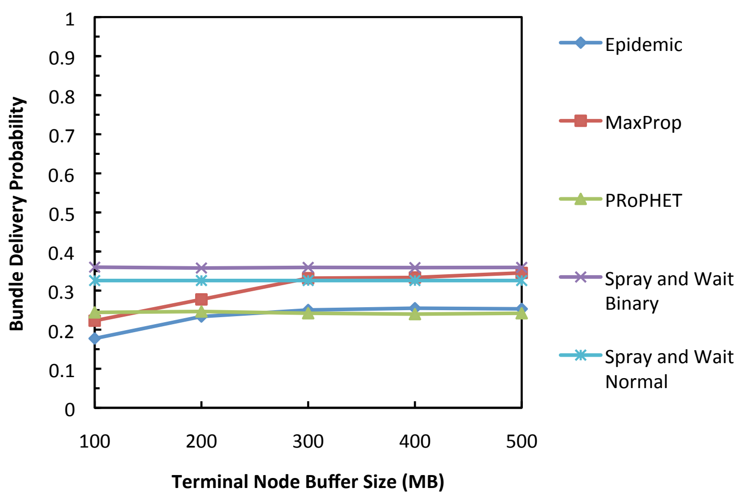

Figure 5.19: Bundle delivery probability as function of terminal nodes buffer size for Epidemic, MaxProp, PRoPHET, Binary and Normal Spray and Wait routing protocols, using 12 mobile nodes with 200 MB buffer size.

When mobile nodes' buffer size is increased to 400 MB (shown in Figure 5.20), the bundle delivery probability of all routing protocols increases. As it can be observed, comparing results of Figure 5.17 to those of Figure 5.20, the performance difference between the two variants of Spray and Wait has increased. The binary variant is more efficient, and when twelve mobile nodes with 400 MB buffers are deployed, it achieves better delivery probabilities than the other considered routing protocols. Figure 5.20 also shows that Epidemic and MaxProp take advantage of larger buffers. In this case, the network load produced by Epidemic has less effect on the bundle delivery probability because of the larger storage capacity available on the mobile nodes.

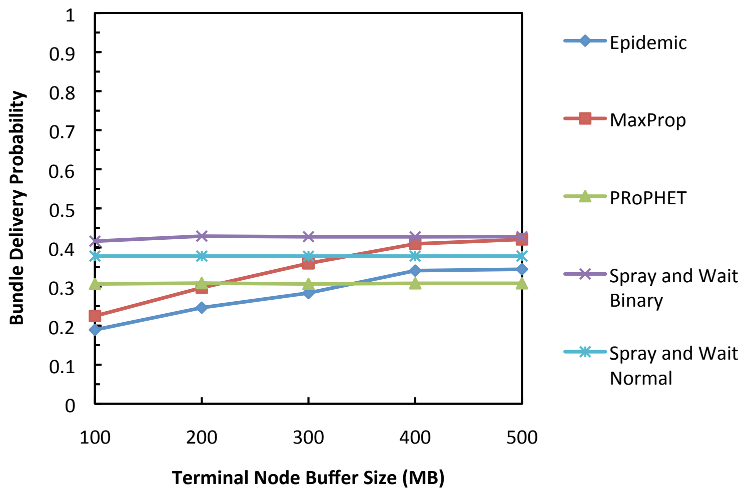

Figure 5.20: Bundle delivery probability as function of terminal nodes buffer size for Epidemic, MaxProp, PRoPHET, Binary and Normal Spray and Wait routing protocols, using 12 mobile nodes with 400 MB buffer size.

Scenario with 18 Mobile Nodes

In the third scenario under study, the number of mobile nodes is increased to 18, each initially with a 200 MB buffer. This also increases the number of opportunistic contacts, reducing the inter-contact times, and improving the overall connectivity. Hence, this has a positive impact on the bundle delivery probability for all routing protocols, as shown in Figure 5.21.

An analysis of these results reinforces that Epidemic flooding scheme is limited by the amount of storage available at mobile nodes. Eighteen mobile nodes create more transmission opportunities. Therefore more bundles will be exchanged and buffer congestion will occur more often. The MaxProp protocol explicit bundle clearing after delivery, allows it to make a better use of the network nodes' storage and bandwidth resources. When terminal nodes' buffer size is equal or greater than 300 MB, MaxProp registers slightly better delivery probabilities than the other protocols. Because of the fixed and limited number of copies created per bundle, Spray and Wait protocol does not benefit from the increase of the buffer size in the terminal nodes.

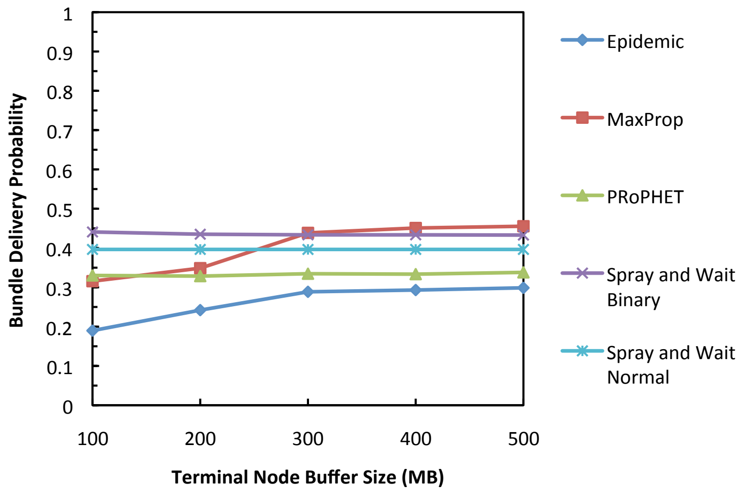

Figure 5.21: Bundle delivery probability as function of terminal nodes buffer size for Epidemic, MaxProp, PRoPHET, Binary and Normal Spray and Wait routing protocols, using 18 mobile nodes with 200 MB buffer size.

Figure 5.22 also reinforces the importance of the storage capacity on mobile nodes. Since vehicles are opportunistically exploited to offer a bundle relaying service, increasing their buffer size to 400 MB augments the probability of bundles to be successfully delivered. Even Spray and Wait routing protocol takes advantage from the possibility of mobile nodes to store and transport more bundles between terminal nodes, increasing its performance in comparison with results presented in Figure 5.21.

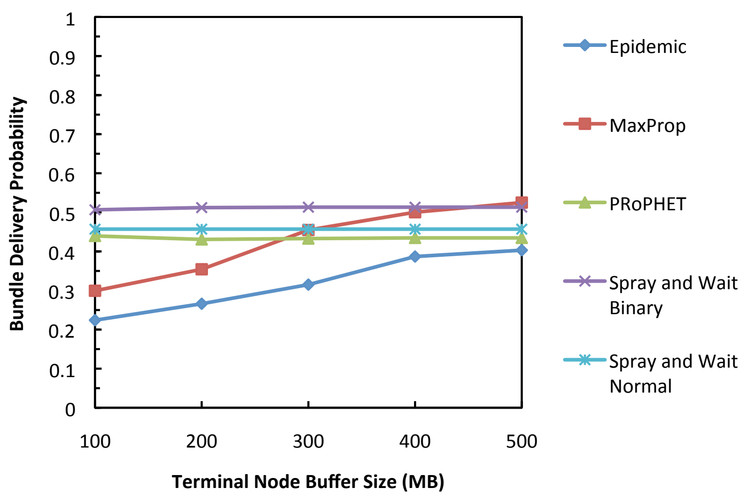

Figure 5.22: Bundle delivery probability as function of terminal nodes buffer size for Epidemic, MaxProp, PRoPHET, Binary and Normal Spray and Wait routing protocols, using 18 mobile nodes with 400 MB buffer size.

5.6. Summary

In many remote or undeveloped areas, and in undeveloped countries, the high cost and/or environmental conditions prohibit the construction of any durable network infrastructure, and the use of effective traditional wireless technologies. In such scenarios, DTN based networks are viewed as a viable solution in the foreseeable future to provide data communications. Several examples of DTN projects, including possible applications of VDTNs, to provide rural connectivity were presented in this Chapter.

The Chapter focused on aspects that can influence the performance of a VDTN network applied to such scenarios. First, the performance metrics under consideration were defined in Section 5.2. In Section 5.3, it was evaluated the role of stationary relay nodes in complementing the store-carry-and-forward strategy. Simulations were conducted to evaluate the impact of adding stationary relay nodes in the performance of four well-known and widely investigated routing protocols considered in this study (Epidemic, MaxProp, PRoPHET, and Spray and Wait). The results confirmed the importance of these nodes to increase the number of transmission opportunities in sparse networks with a low mobile node density, and their significant effect in improving the bundle delivery probability and the bundle average delivery delay. It is worth to notice that simulation studies considered an opportunistic environment without knowledge of the traffic matrix and contact opportunities. If information about contact opportunities and traffic matrix was previously available, the relay nodes placement could be considered simultaneously with routing and the network performance would be enhanced [36, 206].

In Section 5.4, it was analyzed how different mobility patterns and vehicle densities influence the performance of routing protocols with different replication strategies (Epidemic, MaxProp, PRoPHET, and Spray and Wait), in terms of bundle delivery probability and bundle average delivery delay. In addition, the routing protocols parameters were varied across the simulations to study their effect on these performance metrics.

The effect of storage constraints on the performance of routing protocols (Epidemic, MaxProp, PRoPHET, and Spray and Wait) in terms of bundle delivery probability was studied in Section 5.5. Simulation experiments were conducted in scenarios with different node densities varying the buffer size of mobile nodes and terminal nodes. The results show that routing protocols replication strategies react differently to the increase of buffer size in specific network nodes. For example, Epidemic and MaxProp protocols benefit from the increased storage capacity in all network nodes, while Spray and Wait only improves the bundle delivery probability if the mobile nodes buffer capacity is increased.

Overall, the studies conducted in this Chapter were pertinent to the development of some of the proposals studied in Chapter 6 (e.g., queuing disciplines and GeoSpray routing protocol).

Chapter 6

Improving the Performance of VDTNs

6.1. Introduction

This Chapter addresses the study of techniques proposed to improve the performance of vehicular delay tolerant networks, namely, node localization, node cooperation, scheduling and dropping policies, traffic differentiation, and routing. The performance evaluation of these techniques is conducted by simulation, using the VDTNsim simulation tool described in Section 4.2. Moreover, this Chapter also presents a testbed-based performance evaluation study of DTN routing protocols applied to VDTNs, through the VDTN@Lab testbed presented in Section 4.3.

The outline of this Chapter is as follows. Section 6.2 presents the performance metrics considered in the simulation and testbed studies reported in this Chapter. Section 6.3 evaluates the role of node localization (described in Section 3.3) on improving the use of data plane resources, and its impact on the bundle delivery probability and the bundle average delivery delay. The impact of nodes' cooperative behavior in the bundle delivery probability and the bundle average delivery delay observed for Epidemic and Spray and Wait routing protocols is studied in Section 6.4. Section 6.5 analyzes the impact of different scheduling policies and dropping policies on the bundle delivery probability and the bundle average delivery delay. Section 6.6 evaluates the performance of the mechanisms for supporting traffic differentiation presented in Section 3.4, in terms of the number of delivered and dropped bundles per priority class. The performance evaluation of the proposed routing protocol described in Section 3.5, called GeoSpray, is presented in Section 6.7. The performance of GeoSpray is compared with common routing protocols for DTN-based networks (First Contact, Direct Delivery, Epidemic, Binary and Source Spray and Wait, PRoPHET, and GeOpps), in terms of bundle delivery probability, bundle average delivery delay, number of initiated bundle transmissions, number of dropped bundles, overhead ratio, average hop count, and average buffer time. Section 6.8 presents a study conducted in a testbed to demonstrate and evaluate the performance of First Contact, Direct Delivery, Epidemic, Spray and Wait, and PRoPHET routing protocols in VDTN networks. Finally, Section 6.9 concludes the Chapter presenting the main conclusions.

Like in the previous Chapter, thirty simulation runs with different random seeds were performed for each simulation setup. The plots also show only the mean values of the simulation runs, since the standard deviations were negligible.

Part of this Chapter was published in [50-56].

6.2. Performance Metrics

This Section describes the following eight performance metrics used to evaluate the network performance: contact duration, number of initiated bundle transmissions, number of relayed bundles, number of dropped bundles, number of delivered bundles, overhead ratio, average hop count, and average buffer time. The number of contacts per hour, the bundle delivery probability, and the bundle average delivery delay performance metrics were already described in Section 5.2.

Contact duration: It is defined as is the time between the beginning and the end of a contact, i.e., the time while two nodes are in range of each other.

Number of initiated bundle transmissions: It is defined as the total number of started bundle transmissions between network nodes (at node encounters). Note that if a multiple-copy routing scheme is considered, then one bundle can cause multiple transmissions due to its possible replication.

Number of relayed bundles: It is defined as the total number of bundles that have been successfully relayed between network nodes (i.e., does not count bundle fragments).

Number of dropped bundles: It is defined as the total number of bundles that have been discarded from the nodes' buffers due to buffer overflow or TTL expiration.

Number of delivered bundles: It is defined as the total number of unique bundles that have been successfully delivered to the destination node(s) (i.e., does not count bundle replicas).

Overhead ratio: It is a measure of the bandwidth efficiency of a routing protocol. It measures how many "extra" bundle transfers were needed for each bundle delivery. It is calculated according to Equation 6.1, where *OR* is the overhead ratio, *Rb* is the total number of successfully transmitted (i.e., relayed) bundles between the network nodes, and *Db* is the total number of unique delivered bundles.

$$OR = \frac{Rb - Db}{Db} \tag{6.1}$$

Average hop count: It is defined as the average number of hop counts between the source node and the destination node of bundles.

Average buffer time: It is defined as the average time that bundles stay in the nodes' buffers, from creating/receiving them until they are dropped or removed.

6.3. Impact of Node Localization on the Network Performance

This Section presents a study to evaluate the influence of using node localization information on the performance of VDTN networks. The control plane performs this specific function, which was presented in Section 3.3. It aims to prevent incomplete transmissions and optimize the use of network resources at the data plane level. The performance metrics considered are the number of relayed bundles, the bundle delivery probability, and the bundle average delivery delay.

6.3.1. Network Scenario

The simulation scenario is based on a map-based model of a part of Helsinki (Finland) presented in Figure 6.1. During a 12 hours period of time (e.g., from 8:00 to 20:00), 100 mobile nodes (i.e., vehicles) move along the map roads between random locations. Their average speed changes between 20, 30, 40, and 50 km/h, across the simulations, and they have random pause times between 5 and 15 minutes. Each of the mobile nodes has a 100 MB buffer. Five stationary relay nodes are placed at the road intersections presented in Figure 6.1, to increase the number of contact opportunities. Each of the stationary relay nodes has a 500 MB buffer.

Data bundles with sizes uniformly distributed in the ranges of [25 KB, 100 KB], [250 KB, 500 KB], and [750 KB, 1 MB] (bytes) are sent from random source to random destination mobile nodes, at intervals uniformly distributed in the range [25, 35] seconds. These bundles represent aggregates of traffic generated by different VDTN applications, and have a time-to-live of 60 minutes. TTL is a timeout value that expresses when bundles should be discarded from nodes' buffers, since they are no longer meaningful.

Network nodes exchange signaling information using a link connection with an omni-directional transmission range of 90 meters. Data bundles are transmitted using a link with a data rate of 4.5 Mbps and an omni-directional transmission range of 30 meters, as proposed in [275]. Binary Spray and Wait [202] is used as the underlying bundle routing scheme and a maximum of 16 bundle copies is considered.

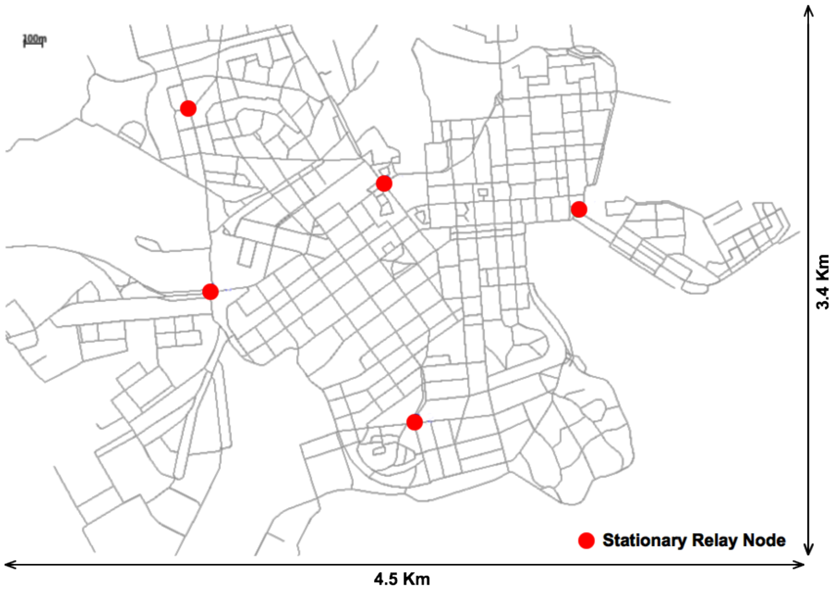

Figure 6.1: Illustration of the Helsinki downtown (Finland) simulation scenario, with the locations of the stationary relay nodes.

6.3.2. Performance Assessment

The results observed in the simulation experiments demonstrate the importance of the approach introduced by the VDTN architecture to sparse vehicular networks. Figure 6.2 shows that the majority of contacts registered in the network occurred between mobile nodes. Only few contacts between mobile nodes and relay nodes were observed. Since it is envisioned that relay nodes are power-limited because they run on solar panels or batteries, it is essential to optimize their energy consumption.

With the introduction of control and data planes separation (using out-of-band signaling), VDTN architecture enables stationary relay nodes to spend little energy while searching for contact opportunities. Moreover, their high-power, high bandwidth, short-range link that is used to transmit and receive data bundles, is active only during the small amount of time that last contacts. This allows extending battery life of these nodes, which have an important role in increasing the overall performance of the network in terms of the bundle delivery probability and the bundle average delivery delay [46], as shown in Section 5.3.

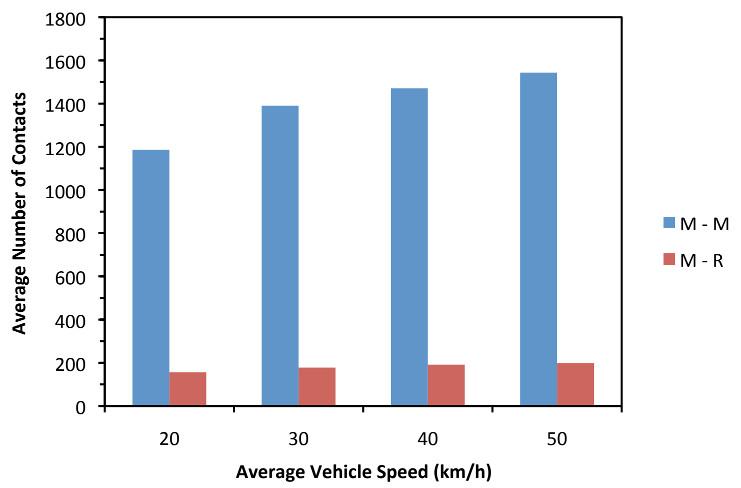

Figure 6.2: Average number of contacts registered between mobile nodes (M – M) and between mobile nodes and relay nodes (M – R) as function of average vehicle speed.

Figure 6.3 shows that the use of node localization function improves the data plane link utilization, increasing the number of successfully relayed bundles between network nodes. As expected, the analysis of this figure also reveals that increasing the average vehicles speed decreases the number of relayed bundles due to the shorter contact duration times. Nevertheless, the performance benefit of using node localization increases when vehicles move with greater average speeds.

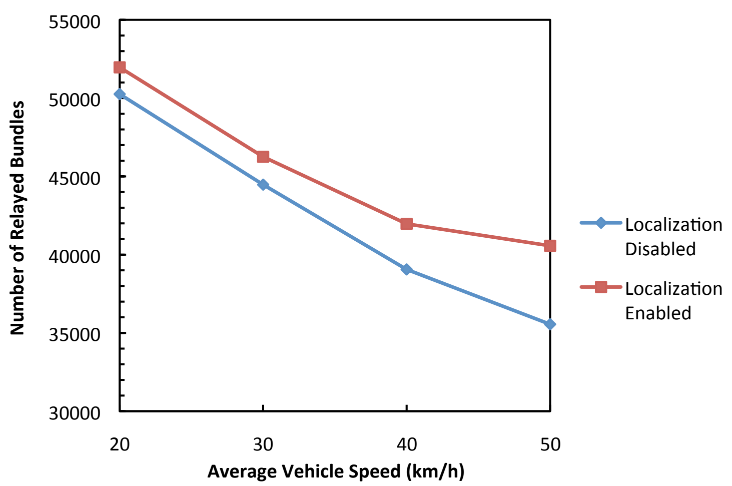

Figure 6.3: Number of relayed bundles as function of average vehicle speed when node localization function is disabled or enabled.

By increasing the number of successfully relayed bundles, the nodes will store, carry, and forward more bundles. As may be observed in Figure 6.4, this results in increasing the bundles' probability to be successfully delivered to their final destination very significantly. In addition, Figure 6.5 shows that the node localization function also contributes to decrease the bundle average delivery delay considerably. The analysis of these figures shows that, for example, when vehicles move at an average speed of 50 km/h, the bundle delivery probability increases about 11% and these bundles arrive at their destination approximately 6 minutes (i.e., 10%) sooner (in average).

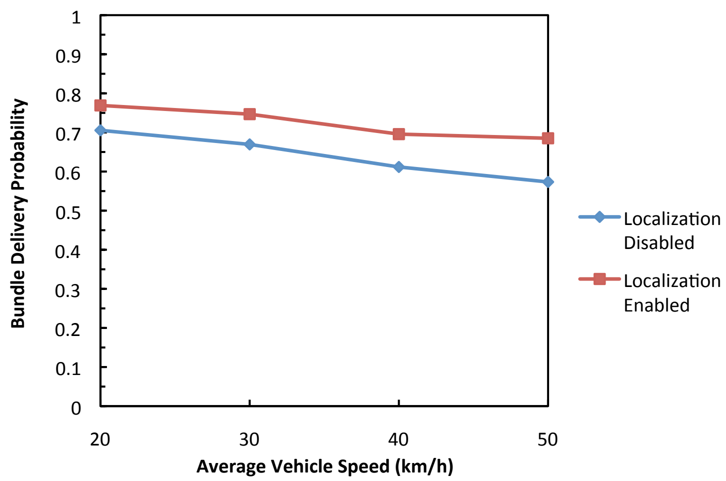

Figure 6.4: Bundle delivery probability as function of average vehicle speed when node localization function is disabled or enabled.

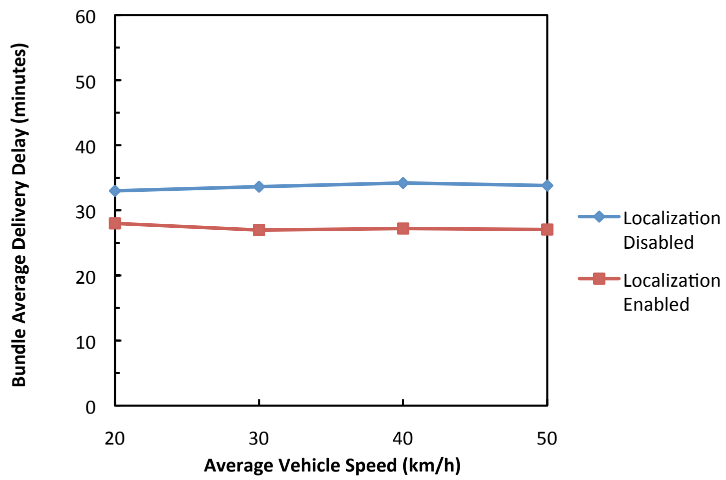

Figure 6.5: Bundle average delivery delay as function of average vehicle speed when node localization function is disabled or enabled.

6.4. Effect of Cooperation on the Network Performance

Following delay-tolerant networks, vehicular delay-tolerant networks also take advantage of the benefits introduced by the cooperative behavior of network nodes in order to obtain significant enhancement of the network performance. In particular, all VDTN network functions are based on the principle of cooperation between network nodes. This encompasses the strategies for signaling and resources reservation. But cooperation is not restricted only to the control plane. At the data plane level, network nodes rely on mutual cooperation (and node mobility) to relay bundles between source and destination nodes. However, network nodes are constrained with limited data plane resources, such as storage and link bandwidth. In this sense, a fully cooperative behavior, such as unconditionally store and forward bundles for others, cannot be taken for granted. Nodes might not be willing to unconditionally store all bundles sent by other network nodes, in order to save buffer resources for their own bundles. The same applies to scheduling bundle forwarding. For instance, network nodes might give preference to scheduling first all their own bundles for transmission. Such a behavior may limit severely the relaying of the other nodes' bundles due to short-lived links and finite bandwidth.

This Section studies the impact of node cooperation at the data plane level. More concretely, at the data plane, it is assumed that nodes' resources (e.g., storage and bandwidth) will be divided into two parts. One part of the nodes' resources is reserved to store and forward their own bundles, whereas the other part is used for cooperation purposes. The influence of different amounts of data plane resources reserved for node cooperation on the network performance is evaluated. The performance metrics considered are the bundle delivery probability and the bundle average delivery delay.

6.4.1. Network Settings

For the simulation scenario, it is used a map-based model of a small part of the city of Helsinki (Finland) presented in Figure 6.6. Stationary relay nodes were placed at five road intersections presented in this figure, each one with a 500 MB buffer. During a 12 hours period of time (e.g., from 8:00 to 20:00), 100 mobile nodes (vehicles) move on the map roads at an average speed of 30 km/h, between random locations, with random pause times between 5 and 15 minutes. Different storage constraints are introduced by changing the mobile nodes buffer size between 25, 50, 75, and 100 MB, across the simulations. Network nodes use a data plane link connection with a transmission data rate of 6 Mbps and an omni-directional transmission range of 30 meters.

Data bundles are generated using an inter-bundle creation interval that is uniformly distributed in the range of [15, 30] seconds and have random source and destination vehicles. Data bundles size is uniformly distributed in the range of [250 KB, 2 MB] (bytes), and they have a time-to-live (TTL) of 180 minutes. Data bundles are discarded in cases of buffer congestion or when TTL expires. Epidemic [200] and Binary Spray and Wait [202] (assuming 8 bundle copies) are used as the underlying routing schemes.

The performance results are evaluated when mobile nodes employ 10, 20, 30, 40, or 50% of their buffer capacity and bandwidth resources, to cooperate in bundle relay.

Figure 6.6: Illustration of the Helsinki (Finland) simulation scenario (area of 4500x3000 meters), with the locations of the stationary relay nodes (R).

6.4.2. Performance Results

Scenario with Epidemic Routing Protocol

First, the results analysis focuses on the bundle delivery probability observed for Epidemic routing protocol. Figure 6.7 shows the effect of node cooperation percentage, from 10% up to 50%, on the bundle delivery probability. It can be observed that this routing protocol registers low bundle delivery probability values across all the simulations. These results are due to Epidemic's pure flooding approach that wastes network resources and severely degrades the overall network performance when resources are scarce. Increasing the cooperation percentage at network nodes from 10% up to 20%, results in allowing 20% of the full buffer capacity to be used for storing bundles relayed by other nodes while the remaining 80% will be (always) available to store bundles generated at the nodes. In addition, at a contact opportunity, 20% of the transmission link bandwidth will be used to relay the other nodes bundles, instead of the previous 10%. Hence network nodes will be able to store, carry, and forward more bundles generated by other nodes. As expected, this behavior results in improving the overall network performance in terms of the bundle delivery probability. For example, when network nodes use a 25 MB buffer, increasing the cooperation percentage from 10% to 20%, results in improving the bundle delivery probability about 13%.

Increasing the buffer size of network nodes attenuates the high buffer occupancy utilization problem of this routing protocol. Moreover, the analysis of Figure 6.7 also allows concluding that a better bundle delivery probability can be obtained using a 25 MB buffer size and a 30% cooperation percentage, instead of a 100 MB buffer with a 10% cooperation percentage.

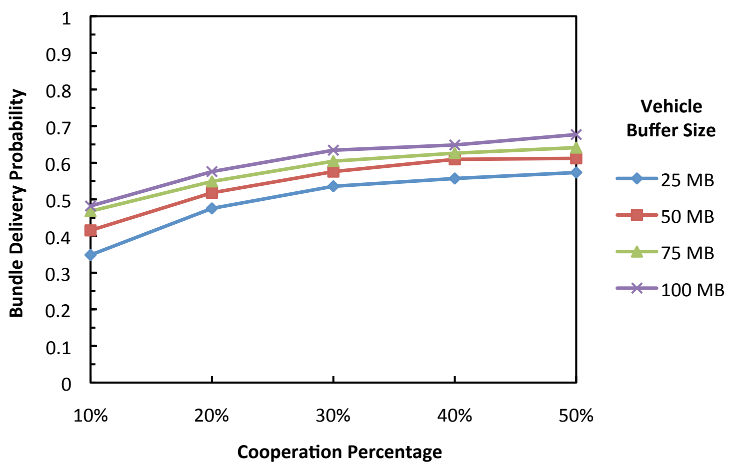

Figure 6.7: Bundle delivery probability for Epidemic routing protocol as function of the cooperation percentage for vehicles buffer sizes of 25, 50, 75, and 100 MB.

As above discussed, by increasing the mobile nodes buffer size, they will be able to store, carry and exchange more bundles during longer periods of time, before being dropped due to buffer overflow or TTL expiration. This contributes to increase the bundle delivery probability (Figure 6.7), but also increases the bundle average delivery delay, as expected and can be observed in Figure 6.8. This effect is reinforced by the increase of the nodes' cooperation percentage that increases the average time that bundles spend in buffers before being delivered or dropped.

An analysis of Figure 6.8 reveals that these conclusions are valid for mobile nodes buffer sizes equal to or greater than 50 MB. When 25 MB buffers are used, two distinct behaviors can be observed. When cooperation percentage is lower than 20%, the storage space available for cooperating in the bundle relay process is very close to the average bundle size, which results in a very low number of cooperative bundles stored, and leads to frequent drops of such bundles. This behavior is very pronounced at 10% cooperation percentage. As a consequence, most of the delivered bundles are transmitted from the source mobile nodes themselves, which results in a bundle average delivery delay greater than the one registered for the other buffer sizes.

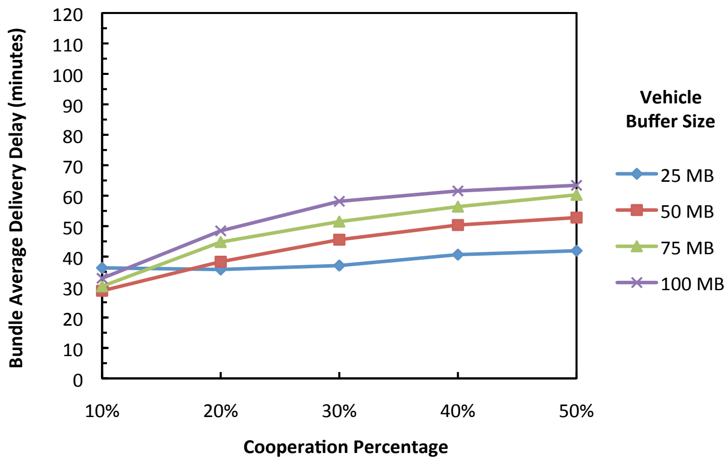

Figure 6.8: Bundle average delivery delay for Epidemic routing protocol as function of the cooperation percentage for vehicles buffer sizes of 25, 50, 75, and 100 MB.

Scenario with Spray and Wait Routing Protocol

Spray and Wait routing strategy reduces transmissions by bounding the total number of copies/transmissions per bundle. Hence, it succeeds in limiting some of the overhead of the pure epidemic diffusion. Therefore, as expected, Spray and Wait performs better than Epidemic, presenting higher delivery probabilities across all simulations in this resource constrained network scenario. This can be seen by comparing the results of Figures 6.7 and 6.9.

The effect of cooperation, as an effective strategy to increase the bundle delivery probability, is even more pronounced in this routing protocol. Figure 6.9 shows that when mobile nodes have a 25 MB buffer size, changing the cooperation percentage from 10% to 50%, increases the bundle delivery probability in approximately 19%, 12%, 8%, and 7%, respectively. In addition, as can be seen in this figure, employing a 100 MB buffer with a 10% cooperation percentage results in a similar bundle delivery probability to a 25 MB buffer with a 40% cooperation percentage. The analysis of this figure also allows concluding that increasing cooperation above 20% when 75MB or 100 MB buffer sizes are used, does not improve the bundle delivery probability significantly for this simulation scenario.

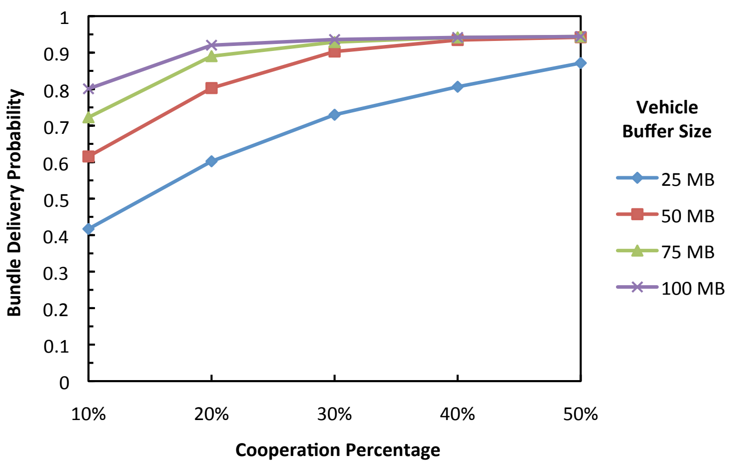

Figure 6.9: Bundle delivery probability for Spray and Wait routing protocol as function of the cooperation percentage for vehicles buffer sizes of 25, 50, 75, and 100 MB.

Spray and Wait routing protocol not only registers higher delivery probabilities, but also achieves better delivery delays (Figure 6.10) than previously shown for Epidemic flooding-based routing (Figure 6.8). Moreover, as it can be observed from the analysis of Figures 6.9 and 6.10, increasing the buffer size of mobile nodes and/or the cooperation percentage, it increases the bundle delivery probability. However, it has no significant effect on the bundle average delivery delay registered for Spray and Wait. Figure 6.10 also shows that similar bundle average delivery delays are registered for buffer sizes greater than 25 MB and cooperation percentages greater than 20%. This behavior was expected since similar delivery probabilities are observed in these cases.

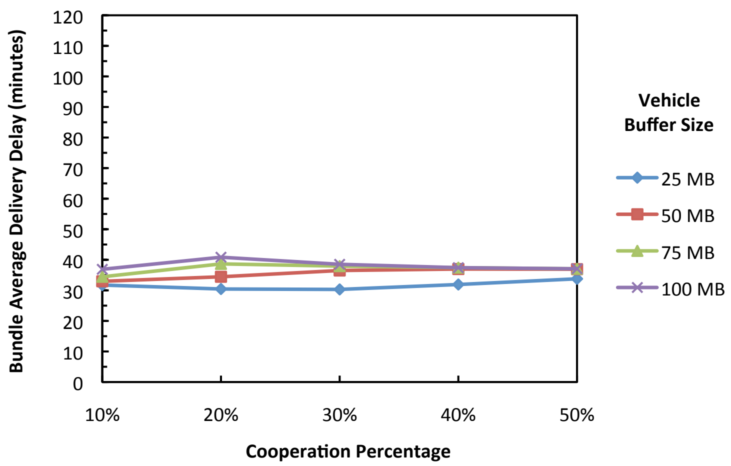

Figure 6.10: Bundle average delivery delay for Spray and Wait routing protocol as function of the cooperation percentage for vehicles buffer sizes of 25, 50, 75, and 100 MB.

6.5. Impact of Queuing Disciplines on the Network Performance

VDTNs are characterized by very high node mobility, which results in frequent topological changes and network partition. In these networks, the node density and the mobile nodes mobility pattern have a direct effect over the observed transmission opportunities, contact durations, and inter-contact times.

Figures 6.11 and 6.12 illustrate the effect of the mobile nodes (i.e., vehicles) density and their average speed in a network scenario detailed in Subsection 6.5.2. Figure 6.11 shows that the number of contact opportunities is directly related to the number of mobile nodes available on the network, as expected. Moreover, it allows concluding that the number of contact opportunities grows as the mobile nodes average speed increases. As may be seen, this effect is more pronounced for the scenario with 50 mobile nodes.

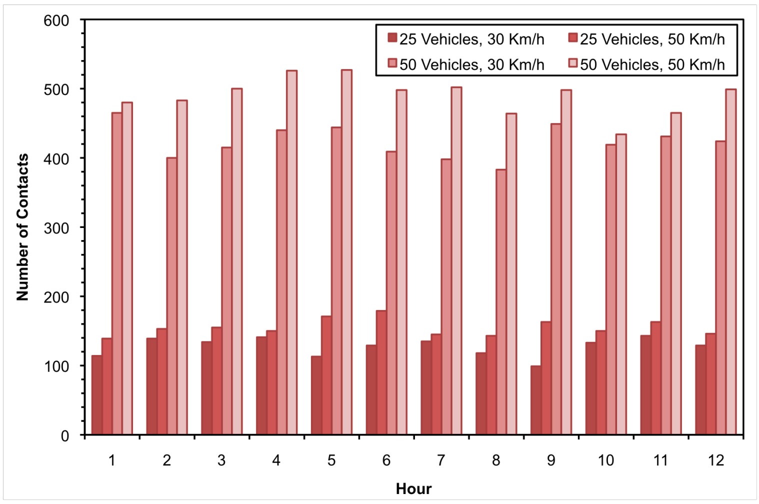

Figure 6.11: Number of contacts per hour between network nodes, with 25 or 50 vehicles moving at an average speed of 30 km/h or 50 km/h.

Figure 6.12 shows that network nodes register short contact durations, due to the speed of mobile nodes. As mobile nodes move at a faster speed, more contacts are registered, but the contact duration decreases even more. This impacts bundles transmission since the available bandwidth is further restricted and may turnout to be insufficient to transmit all intended bundles at contact opportunities. Moreover, in such challenging scenarios, long-term storage is often combined with replication-based routing schemes [187]. Spreading multiple copies of bundles to several network nodes improves the delivery rate and reduces the delivery latency. However, in a resource-constrained network, these techniques cause contention for network resources (e.g., bandwidth and storage), and can greatly influence the performance of routing protocols [49, 189, 192]. This emphasizes the need for adequate scheduling policies to sort the bundles to transmit at (brief) contact opportunities and adequate dropping policies to decide which bundles are discarded when buffer space is exhausted.

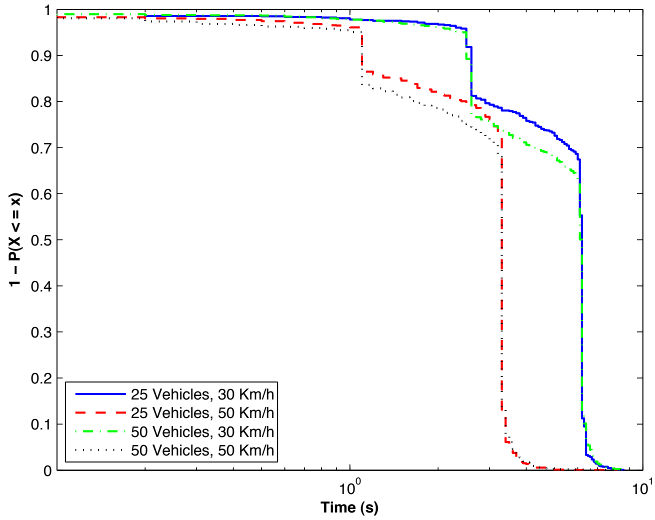

Figure 6.12: Contact durations with 25 or 50 vehicles moving at an average speed of 30 km/h or 50 km/h.

This Section presents a study to evaluate the influence of different combinations of scheduling and dropping policies on the performance of VDTN networks, in terms of the bundle delivery probability and the bundle average delivery delay. The remainder of this Section is organized as follows. Subsection 6.5.1 presents the scheduling and dropping policies studied in this work. Subsections 6.5.2 and 6.5.3 focus on the comparative analysis of the proposed approaches.

6.5.1. Scheduling and Dropping Policies

This Subsection describes several scheduling and dropping policies, and identifies some variations that can be applied to them. Their performance is evaluated and compared through a simulation study presented in the next Subsections.

Scheduling Policies

The following scheduling policies are considered in this study: First In First Out, Random Selection, Remaining Lifetime, and Replicated Copies.

First In, First Out (FIFO): FIFO sorts bundles to be transmitted at a contact opportunity based on their arrival time to the node's buffer, using a first-come, first-served scheme.

Random Selection (Random): Due to short contact duration and finite bandwidth, FIFO approach may only serve bundles that arrived first to the node's buffer. To avoid this situation, random scheduling policy selects bundles randomly within a queue.

Remaining Lifetime (RL): Both FIFO and Random scheduling policies do not take into account the time-to-live (TTL) of bundles. TTL is a timeout value that expresses the amount of time that bundles should be stored before being discarded, since they are no longer meaningful. Remaining Lifetime scheduling policy sorts bundles based on their remaining TTL. Two variations of this scheduling policy are considered, either *i)* bundles with smaller remaining TTLs are scheduled to be sent first (RL Ascending Order) or *ii)* bundles with longer remaining TTLs are scheduled to be sent first (RL Descending Order).

Replicated Copies (RC): This scheduling policy assumes that nodes keep track of the number of times each bundle has been replicated. Hence, two variations of RC policy may be considered. On the first, bundles that have been less replicated are scheduled to be sent first (RC Ascending Order) or, in the second, bundles that have been more replicated are scheduled to be sent first (RC Descending Order).

Both Remaining Lifetime and Replicated Copies scheduling policies need a tiebreaking rule. In the case of RL scheduling policy, a node may store in its buffer more than one bundle with the same remaining lifetime. The same happens with RC scheduling policy, where a node may store bundles that have been replicated the same number of times. FIFO or Random scheduling policies can be applied to tiebreak these cases.

Dropping Policies

The following dropping policies are considered in this study: Drop Head, Random Selection, Remaining Lifetime, and Replicated Copies.

Drop Head: This dropping policy discards the bundle that has been stored for the longest period of time in the node's buffer, creating available space for the next incoming bundle.

Random Selection (Random): When a receiving buffer is congested, this dropping policy randomly selects one of the bundles within a queue to be dropped.

Remaining Lifetime (RL): Remaining Lifetime dropping policy selects bundles to be discarded based on their remaining TTL. Two variations of this policy are considered, either *i)* the bundle with the smallest remaining TTL is discarded first (RL Ascending Order) or *ii)* the bundle with the longest remaining TTL is discarded first (RL Descending Order).

Replicated Copies (RC): When buffer overflow occurs, the number of times each bundle has been replicated can be used to decide which bundle should be dropped. The following two variations of RC dropping policy may be used: *i)* the bundle that has been less replicated is dropped first (RC Ascending Order) or *ii)* the bundle that has been more replicated is dropped first (RC Descending Order).

For the above reasons, a tiebreaking rule must be used for both Remaining Lifetime and Replicated Copies dropping policies. FIFO or Random scheduling policies can be applied to tiebreak.

6.5.2. Network Setup

The simulation scenario is based on a map-based model of a part of the city of Helsinki (Finland) presented in Figure 6.13. During a 12 hours period of time (e.g., from 8:00 to 20:00), mobile nodes (i.e., vehicles) move along the map roads between random locations, with random pause times between 5 and 15 minutes. To obtain scenarios with different numbers of contact opportunities, the number of mobile nodes changes between 25 and 50 across the simulations. The mobile nodes average speed also changes between 30 km/h and 50 km/h, to obtain scenarios with different contact durations. Each mobile node has a 25 MB buffer. To increase the number of contact opportunities, five stationary relay nodes were placed at the road intersections, as may be seen in Figure 6.13. Each stationary relay node has a 500 MB buffer.

Data bundles are generated using an inter-bundle creation interval that is uniformly distributed in the range of [15, 30] seconds, and have random source and destination vehicles. Data bundles size is uniformly distributed in the range of [250 KB, 2 MB] (bytes). Bundles time-to-live (TTL) changes between 30, 60, 90, 120, 150, and 180 minutes, across the simulations. Bundles are discarded when their TTL expires. Increasing the TTL leads to have more bundles stored at the network nodes' buffers and for longer periods of time. Therefore, more bundles will be exchanged between network nodes, which will increase contention for network resources.

All network nodes use a data plane link connection with a transmission data rate of 4.5 Mbps and an omni-directional transmission range of 30 meters, as proposed in [275]. Binary Spray and Wait [202] is used as the underlying routing scheme and a maximum of 12 bundle copies is defined.

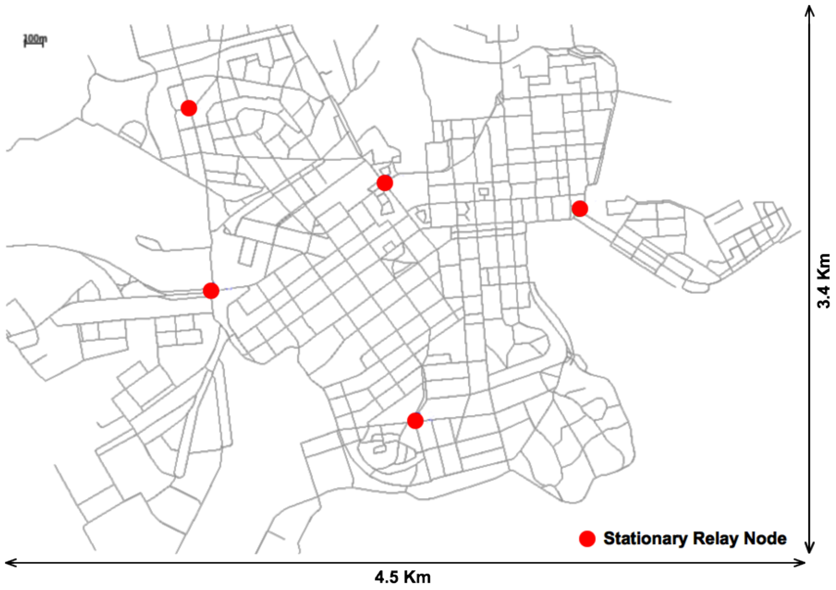

Figure 6.13: Illustration of the Helsinki (Finland) simulation scenario (area of 4500×3400 meters), with the locations of the stationary relay nodes.

The performance metrics considered in this study are the bundle delivery probability and the bundle average delivery delay. The results are shown for the combination of the above described scheduling and dropping policies presented at Table 6.1. A designation for each scheduling and dropping policy pair was created in order to improve plot readability in the results analysis. FIFO policy is used as a base-case of comparison with the other proposed policies.

Designation	Scheduling Policy	Dropping Policy	Tie-break
FIFO	FIFO	Head Drop	-
Random	Random	Random	-
RL ASC	Remaining Lifetime Ascending Order	Remaining Lifetime Descending Order	FIFO
RL DESC	Remaining Lifetime Descending Order	Remaining Lifetime Ascending Order	FIFO
RC ASC	Replicated Copies Ascending Order	Replicated Copies Descending Order	RL DESC
RC DESC	Replicated Copies Descending Order	Replicated Copies Ascending Order	RL DESC

Table 6.1: Combined scheduling and dropping policies.

6.5.3. Results Analysis

Scenario with 25 Vehicles

The evaluation study starts with a comparison of the bundle delivery probability registered when 25 vehicles move with an average speed of 30 km/h. Figure 6.14 shows that when the initial bundles' TTL is lower than 120 minutes, FIFO, Random, RL ASC, and RC DESC policies register similar delivery probabilities. However, when the TTL is greater than 120 minutes, RC DESC policy performs much worse than the other policies. This means that scheduling bundles that have been more replicated to be sent first, is not a good option.

Enforcing a RL DESC policy and, therefore, giving preferential treatment to bundles with larger remaining lifetimes, leads to increase the bundle delivery probability when compared to those policies. Since bundles exchanged between network nodes will have longer remaining lifetimes, this increases their probability to be relayed more times between network nodes, until eventually reaching the destination. This figure shows that when the initial bundles' TTL is equal or lower than 150 minutes, RL DESC increases the bundle delivery probability about 3% for TTL=60min., 5% for TTL=90min., 5% for TTL=120min., 4% for TTL=150min., and 2% for TTL=180min., when compared to the traditional FIFO policy. For a TTL of 180 minutes, RC DESC and FIFO register a similar bundle delivery probability.

RC ASC policy improves these results further. This policy gives preferential treatment to bundles that have been less replicated, using as a tiebreak criterion for bundles that have been replicated the same amount of times, a second scheduling policy - RL DESC. As may be observed, when RC ASC policy is compared to FIFO, it provides up to 3%, 6%, 7%, 6%, 6%, and 5% of gain in the bundle delivery probability, respectively, across all the simulations.

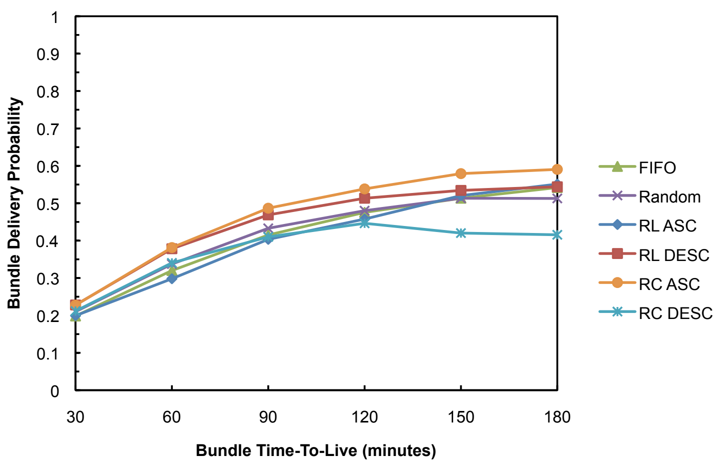

Figure 6.14: Bundle delivery probability as function of bundles TTL in a scenario with 25 vehicles moving at an average speed of 30 km/h for FIFO, Random, RL ASC, RL DESC, RC ASC, and RC DESC combinations of scheduling and dropping policies.

Figure 6.15 shows a comparison between the bundle average delivery delay and the bundles (initial) TTL, for the combinations of scheduling and dropping policies considered. Bundle average delivery delay is an interesting metric, since minimizing the delivery delay reduces the time that bundles spend in the network and, thus, reduces the contention for resources.

As expected, the observed results show that deploying a RL DESC based policy and, therefore, giving preferential treatment to bundles with larger remaining TTLs, decreases the bundle average delivery delay considerably. This policy performs better than the others in this performance metric. On the contrary, the other variant of RL policy - RL ASC - gives preferential treatment to bundles with lower remaining lifetimes, trying to deliver them before expiring. This results in the worst bundle average delivery delays across all the simulations.

FIFO criterion based on the order of bundle arrival to the buffer, also leads to longer bundle average delivery delays. When RL DESC policy is compared to FIFO, bundles arrive at the destination nodes approximately 1, 3, 8, 14, 16, and 18 minutes sooner, in average. As a final note to Figures 6.14 and 6.15, it can be seen that RC ASC outperforms all the other policies in terms of the bundle delivery probability, presenting the second best results in terms of bundle average delivery delay, due to its tiebreak criterion.

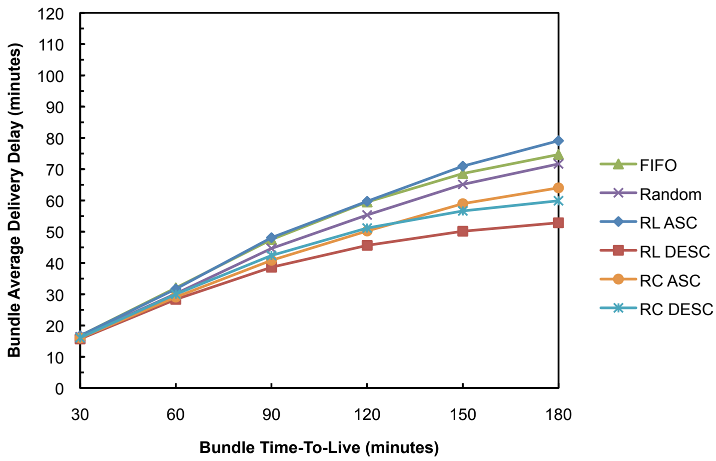

Figure 6.15: Bundle average delivery delay as function of bundles TTL in a scenario with 25 vehicles moving at an average speed of 30 km/h for FIFO, Random, RL ASC, RL DESC, RC ASC, and RC DESC combinations of scheduling and dropping policies.

Although the increase of the vehicles' average speed from 30 km/h to 50 km/h increases the number of contact opportunities (Figure 6.11), it decreases the contact duration time (Figure 6.12). Hence, the number of bundles exchanged during a contact opportunity also decreases. As may be seen through the comparison between the results shown in Figures 6.14 and 6.16, this resulted in lower delivery probabilities for all combinations of scheduling and dropping policies, across all the simulations. In this scenario, the difference in terms of performance between the policies decreases. The values of the bundle delivery probability for RL DESC are close to the ones observed with RC ASC. Nevertheless, Figure 6.16 shows that RC ASC still performs better than the other policies, increasing about 3%, 4%, 8%, 8%, 7%, and 5% the bundle delivery probability for each of the considered values of TTL, when compared to FIFO. Figure 6.17 shows that FIFO and RL ASC present the higher bundle average delivery delay values. The difference in terms of the bundle average delivery delay observed for RL DESC and RC ASC increased for TTLs larger than 90 minutes, when compared to the results shown in Figure 6.15.

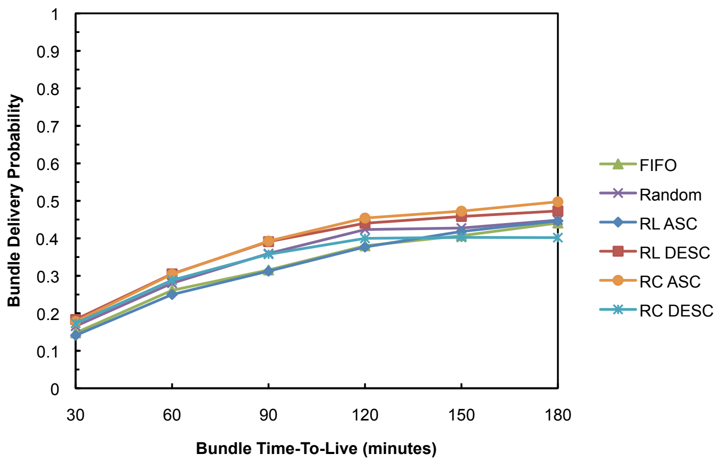

Figure 6.16: Bundle delivery probability as function of bundles TTL in a scenario with 25 vehicles moving at an average speed of 50 km/h for FIFO, Random, RL ASC, RL DESC, RC ASC, and RC DESC combinations of scheduling and dropping policies.

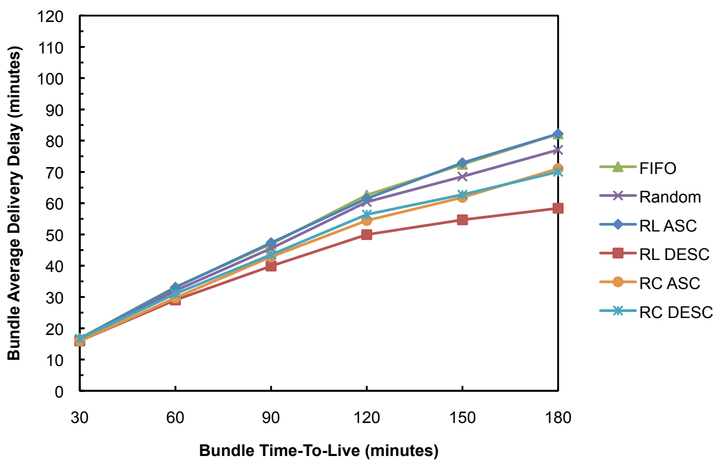

Figure 6.17: Bundle average delivery delay as function of bundles TTL in a scenario with 25 vehicles moving at an average speed of 50 km/h for FIFO, Random, RL ASC, RL DESC, RC ASC, and RC DESC combinations of scheduling and dropping policies.

Scenario with 50 Vehicles

The second scenario considers 50 vehicles moving along the map roads. As shown in Figure 6.11, increasing the node density also increases the number of contact opportunities. This results in increasing the number of relayed bundles and, potentially, causes more contention for network resources. Recall that the traffic generated is equal on both scenarios.

A comparison between the results depicted in Figures 6.14 and 6.18 shows that policies have the same behavior in both scenarios. Moreover, the bundle delivery probability increases for all the considered policies (Figure 6.18), when compared with the first scenario (Figure 6.14). Furthermore, this analysis also reveals that RC ASC registers the best results in terms of the bundle delivery probability, irrespective of the number of mobile nodes. In this second scenario, when vehicles move with an average speed of 30 km/h, it presents gains of 4%, 9%, 6%, 6%, 4%, and 5% for each of the considered values of TTL, respectively, when compared to the FIFO policy (Figure 6.18).

Figure 6.19 confirms the conclusions obtained in the first scenario. Although RC ASC policy requires slightly more time to deliver bundles than RL DESC, it achieves a higher bundle delivery probability (Figure 6.18).

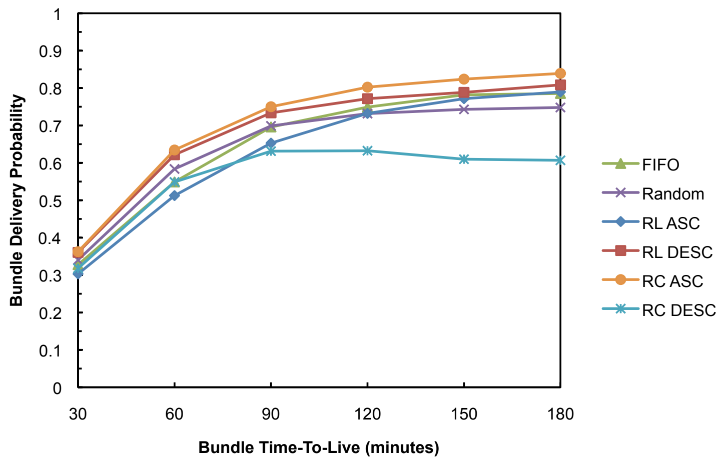

Figure 6.18: Bundle delivery probability as function of bundles TTL in a scenario with 50 vehicles moving at an average speed of 30 km/h for FIFO, Random, RL ASC, RL DESC, RC ASC, and RC DESC combinations of scheduling and dropping policies.

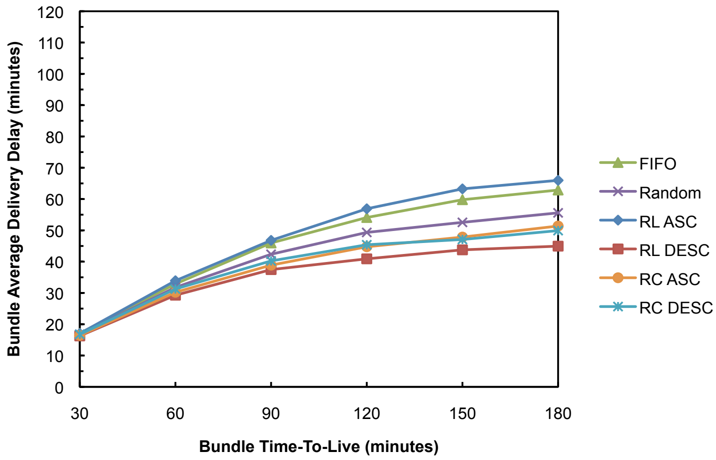

Figure 6.19: Bundle average delivery delay as function of bundles TTL in a scenario with 50 vehicles moving at an average speed of 30 km/h for FIFO, Random, RL ASC, RL DESC, RC ASC, and RC DESC combinations of scheduling and dropping policies.

Following the results shown in the previous scenario, the comparison of Figures 6.18 and 6.20 shows that increasing the vehicles average speed to 50 km/h decreases the number of successfully delivered bundles. However, it is interesting to observe that RC ASC policy is less affected by this change than the remaining policies. Due to this fact, RC ASC shows greatest improvements. Compared to FIFO, RC ASC increases the bundle delivery probability in 6%, 11%, 11%, 10%, 6%, and 7% for each of the considered values of TTL, respectively.

As previously observed, the gains in the bundle delivery probability performance metric are attenuated when bundles have a large TTL. This is due to the fact that network nodes have large buffers and can carry and exchange these bundles during longer periods of time before expiring. However, increasing the TTL reinforces the improvement on the bundle average delivery delay, as can be observed in Figure 6.21. When comparing with FIFO, bundles arrive at the destination nodes approximately 1, 4, 8, 12, 17, and 20 minutes sooner in average, if RC ASC policy is used.

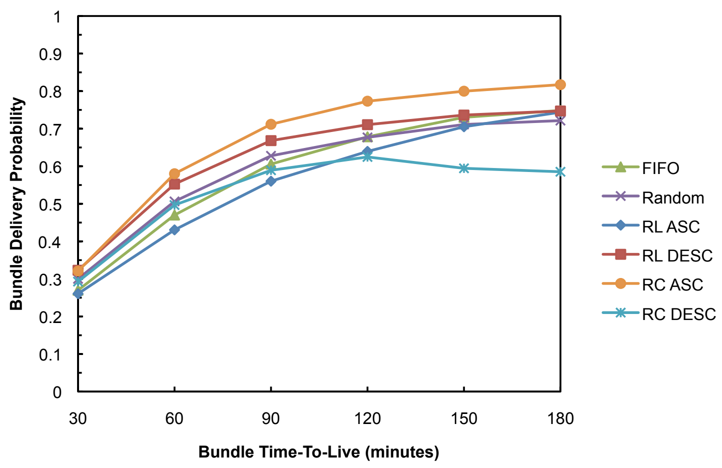

Figure 6.20: Bundle delivery probability as function of bundles TTL in a scenario with 50 vehicles moving at an average speed of 50 km/h for FIFO, Random, RL ASC, RL DESC, RC ASC, and RC DESC combinations of scheduling and dropping policies.

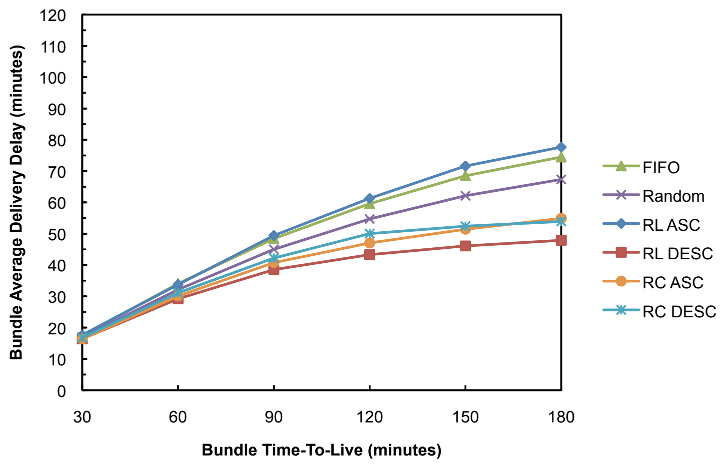

Figure 6.21: Bundle average delivery delay as function of bundles TTL in a scenario with 50 vehicles moving at an average speed of 50 km/h for FIFO, Random, RL ASC, RL DESC, RC ASC, and RC DESC combinations of scheduling and dropping policies.

6.6. Impact of Traffic Differentiation on the Network Performance

In vehicular delay-tolerant networks, traffic prioritization can be used to selectively allocate network resources to services and applications, according to their performance requirements. Traffic differentiation is particularly important when network resources are scarce. In such scenarios, it may be necessary to accommodate and give preference to higher priority traffic, while delaying the processing of lower priority traffic.

This Section studies the impact of the traffic differentiation mechanisms for VDTNs previously presented in Section 3.4. Different buffer management strategies with corresponding dropping policies and scheduling policies are evaluated. The performance analysis considers scenarios with different node densities and under distinctive constraints in terms of contact opportunities, contact durations, and buffer sizes. The study was conducted by simulation. The performance metrics considered are the number of successfully delivered bundles and the number of dropped bundles, per priority class.

6.6.1. Network Parameters

Two simulation scenarios with different node densities are studied. The first scenario considers a network with 25 vehicles, while the second scenario assumes a network with 50 vehicles. For each scenario, a time period of 12 hours (e.g., from 8:00 to 20:00) is simulated. During this period, vehicles move on the roads of a map-based model shown in Figure 6.22, between random locations, and with random stop times between 5 and 15 minutes.

To change the duration of contact opportunities, vehicles move at an average speed of 30 or 50 km/h. Different storage constraints are also introduced by changing the vehicles buffer size between 25, 50, and 100 MB, across all the simulations. Vehicles exchange data between themselves and with the five stationary relay nodes positioned at the road intersections identified in Figure 6.22. All network nodes use a wireless communication link with a data transmission rate of 6 Mbps and a transmission range of 30 meters.

The volume of network traffic is equal on both scenarios. Three bundle event generators are responsible for generating data bundles that correspond to data aggregations with different performance requirements and sizes. In the context of this study, it is assumed that high demanding applications generate larger volumes of traffic. Thus, bundles are generated with sizes uniformly distributed in the ranges of [100 KB, 250 KB] for bulk bundles, [250 KB, 750 KB] for normal bundles, and [750 KB, 1.5 MB] for expedited bundles. Data bundles of each priority class are generated using an inter-bundle creation interval that is uniformly distributed in the range of [15, 30] seconds. In addition, all data bundles have random source and destination vehicles and a time-to-live of 120 minutes. Spray and Wait [202] binary variant is used as the underlying DTN bundle routing scheme, assuming 12 copies to be transmitted (“sprayed”) per bundle.

The performance difference resulting from the combination of the buffer management strategies and scheduling policies presented in Section 3.4 is evaluated for both scenarios. The common buffer strategy is enforced in conjunction with the Priority Greedy (PG) scheduling policy. The buffer management strategy that provides separate storage space for each priority class is used in conjunction with a Custom Service Time (CST) scheduling policy. In this case, it is assumed that 10% of the full buffer space is reserved for bulk bundles, 30%

for normal bundles, and 60% for expedited bundles. In addition, service time percentages assigned to each priority class are also 10% for bulk bundles, 30% for normal bundles, and 60% for expedited bundles. In both scenarios, it is assumed a cooperative opportunistic environment without knowledge of the traffic matrix and contact opportunities.

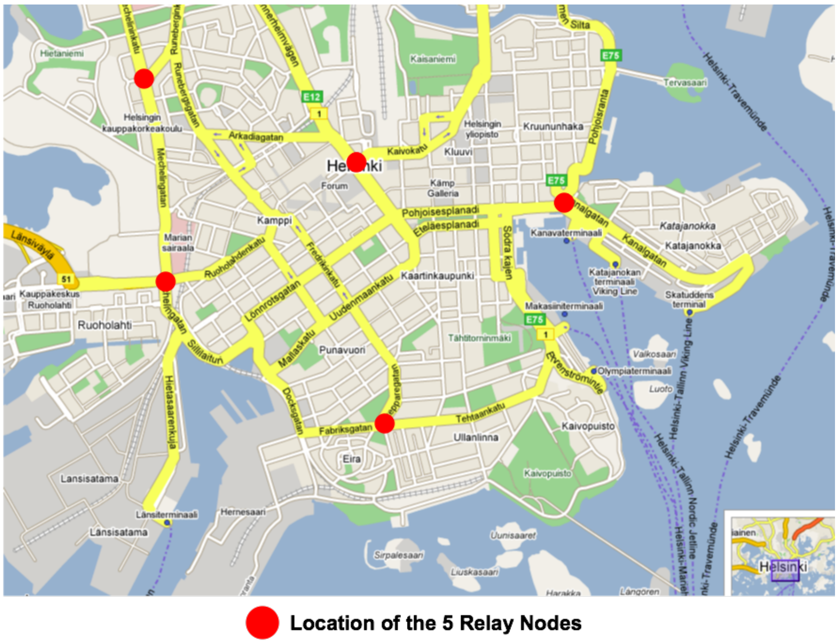

Figure 6.22: Simulation scenario of Helsinki downtown (Finland) area, with a dimension of 4500×3400 meters.

6.6.2. Performance Evaluation

Scenario with 25 Vehicles

The performance analysis starts with the scenario where only 25 vehicles move along the map roads at an average speed of 30 km/h. As may be observed in Figure 6.23, Priority Greedy (PG) policy presents results with the greatest differences between the delivery ratios for each priority class. These ratios are represented as percentages inside the stacked columns. When buffer resources are stringent (25 MB), PG prevents normal and bulk bundles of being stored and relayed between network nodes, since expedited bundles monopolize the existing resources. On the contrary, Custom Service Time (CST) policy guarantees that bundles from all priority classes can be transmitted at contact opportunities. Although a lower number of expedited bundles were successfully delivered for CST (compared to PG), the bundle delivery probability of bulk and normal bundles is greatly enhanced. This behavior is verified across all the simulations for this policy.

Duplicating the buffer size of vehicles to 50 MB, it increases the number of bundles successfully delivered across all priority classes for both scheduling policies, as expected. In the case of the PG policy, the additional buffer space attenuates the resource contention problem caused by its operating principle. Also, it is worth noticing that CST with a 25 MB buffer size presents a sum of delivered bundles greater than the one presented by PG with a 50 MB buffer. By increasing the buffer size to 100 MB, the bundle delivery probability of bulk and normal bundles in PG also increases. Nevertheless, in this case, CST policy only increases the expedited bundles delivery probability slightly.

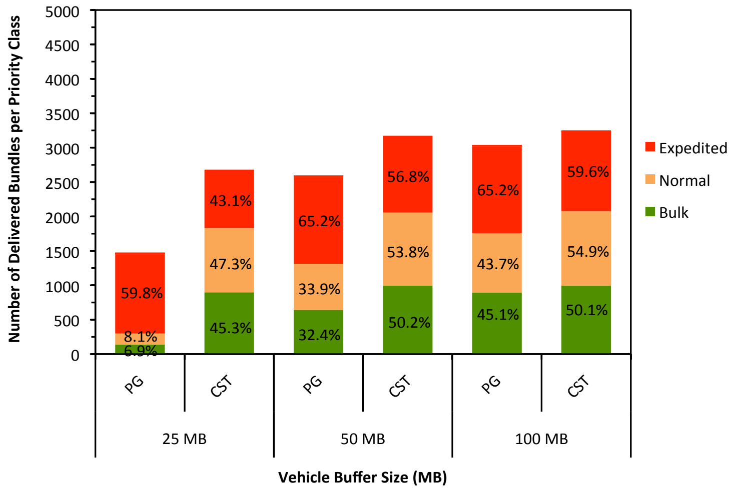

Figure 6.23: Number of delivered bundles per priority class as function of vehicles buffer size for PG and CST scheduling policies, with 25 vehicles moving at an average speed of 30 km/h.

Increasing the vehicles average speed to 50 km/h decreases the contact durations and the number of bundles exchanged during contact opportunities. As may be seen through the comparison between Figures 6.23 and 6.24, this results in lower delivery ratios for all priority classes across all the simulations. This analysis also shows a common trend on the policies performance for both cases.

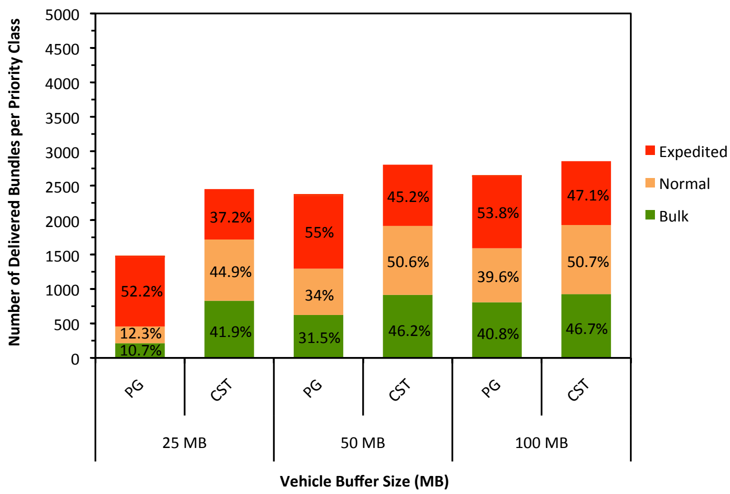

Figure 6.24: Number of delivered bundles per priority class as function of vehicles buffer size for PG and CST scheduling policies, with 25 vehicles moving at an average speed of 50 km/h.

As expected, Figure 6.25 shows that the number of dropped bundles depends on the available buffer capacity. When analyzing the results shown in this figure, it is important to notice that it was assumed that bundles from different priority classes have different sizes, with expedited bundles being the largest ones. At a contact opportunity, CST policy guarantees that bundles from all priority classes are served. Since normal and bulk bundles have smaller sizes, this means that larger numbers of these bundles are possibly exchanged during an encounter between two network nodes. This, in conjunction with (limited) less storage resources assigned to these priority classes, results in contention. Consequently, CST presents the largest sums of dropped bundles across all simulation scenarios. Likewise, the large size of expedited bundles constrains their relaying, and this is reflected in the observed lower numbers of delivered and dropped bundles of this priority class. Finally, when vehicles move at an average speed of 50 km/h, it was observed that the number of dropped bundles was not significantly changed. Hence, these results are not presented here.

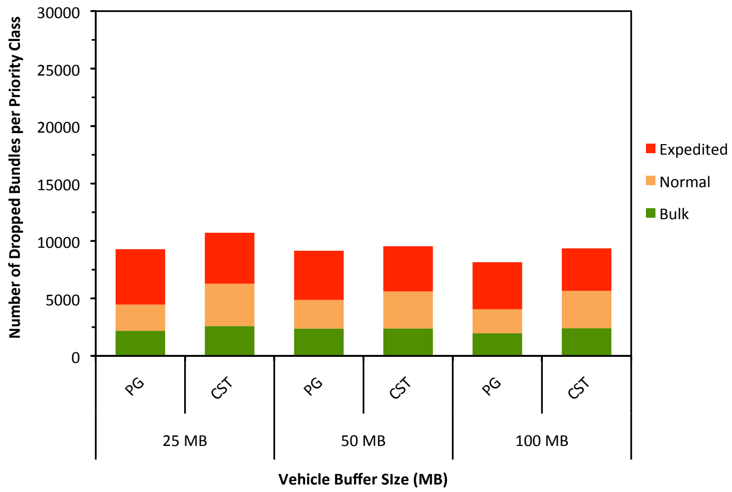

Figure 6.25: Number of dropped bundles per priority class as function of vehicles buffer size for PG and CST scheduling policies, with 25 vehicles moving at an average speed of 30 km/h.

Scenario with 50 Vehicles

The second scenario considers 50 vehicles moving along the map roads. Increasing node density augments the number of contact opportunities. Therefore, network nodes exchange more bundles. On one hand, this increases the probability of bundles to be successfully delivered. But on the other hand, more relayed bundles imply more contention for network resources (e.g., storage and bandwidth).

Figure 6.26 shows that the number of delivered bundles per priority class increases for both policies, across all simulations. Recall that the traffic generated is equal on both scenarios. When compared to the results observed in the first scenario (Figure 6.23), Custom Service Time scheduling policy registers gains of approximately 20% in the delivery ratios of all priority classes, independently of the vehicles buffer size. Priority Greedy also improves the delivery probability of expedited bundles in approximately 20%. However, PG scheduling policy only improves the delivery ratios of normal and bulk bundles considerably when vehicles have 100 MB buffers.

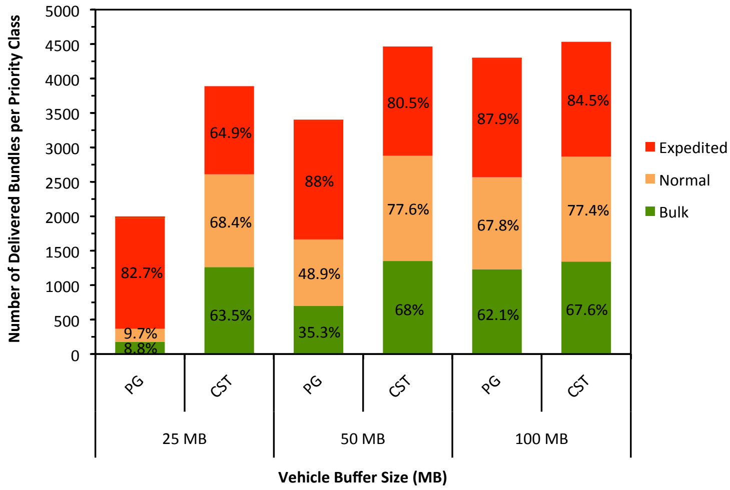

Figure 6.26: Number of delivered bundles per priority class as function of vehicles buffer size for PG and CST scheduling policies, with 50 vehicles moving at an average speed of 30 km/h.

Following the results shown in the previous scenario, increasing the vehicles average speed to 50 km/h lowers the number of successfully delivered bundles per priority class, as can be seen by comparing the results of Figures 6.26 and 6.27. Nevertheless, in this scenario, the observed differences are attenuated by the larger number of contact opportunities.

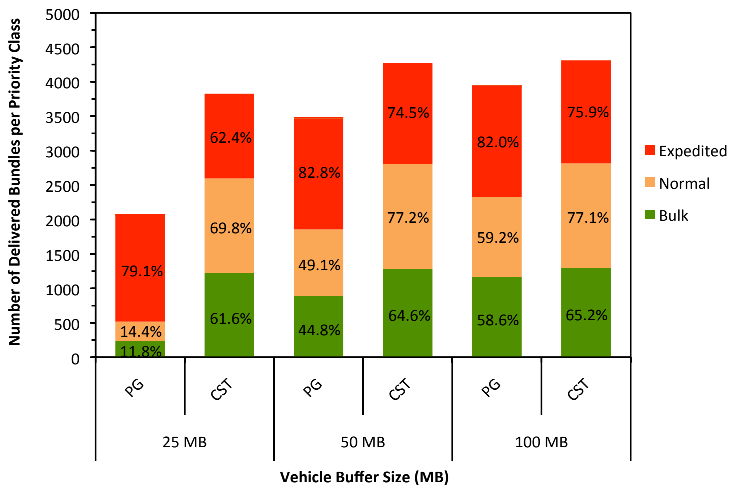

Figure 6.27: Number of delivered bundles per priority class as function of vehicles buffer size for PG and CST scheduling policies, with 50 vehicles moving at an average speed of 50 km/h.

Regarding the number of dropped bundles per priority class, Figure 6.28 shows that introducing 50 vehicles increases the competition for network resources severely. When compared to the values observed in the first scenario (Figure 6.25), PG and CST policies register significantly larger values of dropped bundles. The findings presented in the first scenario, in respect to the low number of dropped expedited bundles, may also be applied here. Although both PG and CST give priority to the treatment of expedited bundles, the large size of these bundles limits their relaying between network nodes. Thus, diminishing the number of delivered and dropped bundles of this priority class.

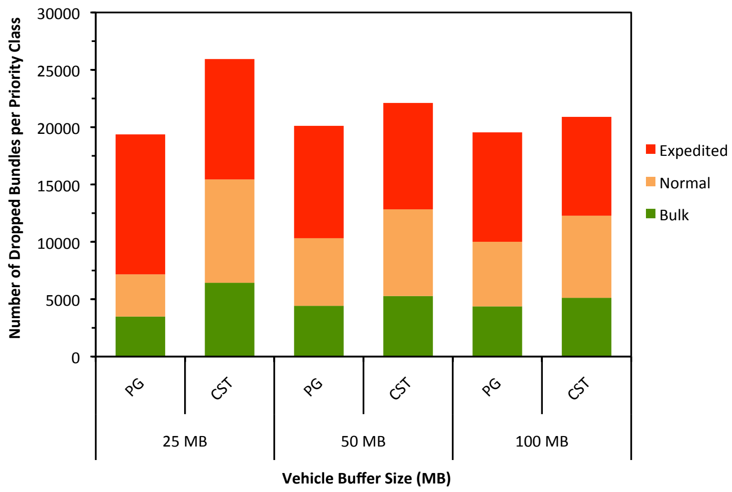

Figure 6.28: Number of dropped bundles per priority class as function of vehicles buffer size for PG and CST scheduling policies, with 50 vehicles moving at an average speed of 30 km/h.

Finally, and unlike in the first scenario, increasing the vehicles average speed to 50 km/h, it affects the number of dropped bundles, as may be seen in Figure 6.29. The sum of dropped bundles decreases in 5000 bundles approximately compared to Figure 6.28, for all the cases evaluated.

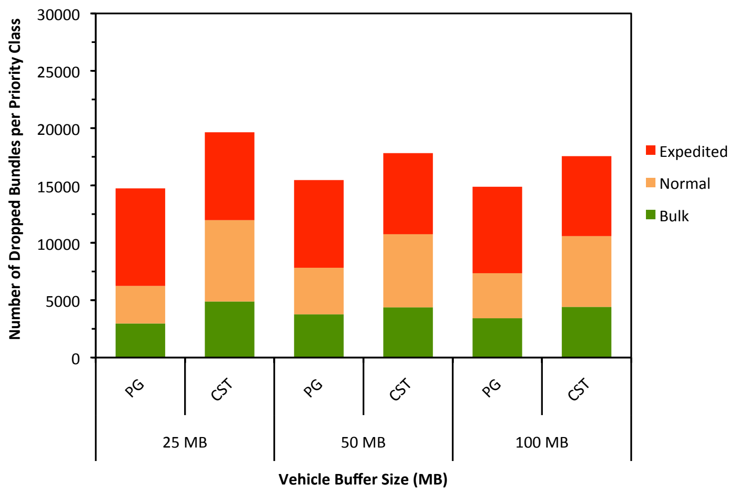

Figure 6.29: Number of dropped bundles per priority class as function of vehicles buffer size for PG and CST scheduling policies, with 50 vehicles moving at an average speed of 50 km/h.

6.7. Performance Assessment of GeoSpray Routing Protocol

GeoSpray is a VDTN routing protocol proposed in this thesis and it was described in Section 3.5. Therefore, it is necessary to evaluate the performance of this new routing protocol in comparison with the above-described DTN routing protocols (First Contact [194], Direct Delivery [196], GeOpps [25], Epidemic [200], Binary and Source Spray and Wait [202], and PRoPHET [203]), which were presented in Subsection 2.3.2. In this sense, this Section presents a study to evaluate the performance of these protocols.

Routing protocols are commonly evaluated according to the main performance metrics bundle delivery probability and bundle average delivery delay. However, for a better understanding of the network resources utilization, this study also analyzes the behavior of the routing protocols in terms of: number of initiated bundle transmissions, number of dropped bundles, overhead ratio, average hop count, and average buffer time. These performance metrics were defined in Sections 5.2 and 6.2.

6.7.1. Network Settings

The network scenario is based on the map-based model of a part of the city of Helsinki (Finland) presented in Figure 6.30. It assumes a fully cooperative opportunistic environment without knowledge of the traffic matrix and contact opportunities.

Ten terminal nodes are placed at the map positions presented in Figure 6.30, each has a 50 MB buffer. During the simulated 6 hours period of time (e.g., from 8:00 to 14:00), mobile nodes (i.e., vehicles) move along the map roads with an average speed of 50 km/h, between random locations, and with random pause times between 5 and 15 minutes. To obtain two scenarios with different numbers of contact opportunities, the number of mobile nodes was changed between 100 and 200 across the simulations. Each mobile node has a 12.5 MB buffer. Five stationary relay nodes were placed at the road intersections shown in Figure 6.30. Each stationary relay node has a 50 MB buffer.

Data bundles are originated at random mobile nodes (i.e., the traffic sources) and are destined to random terminal nodes (i.e., the traffic sinks). To generate data bundles with different sizes (representing traffic created by different VDTN applications), three event generators are considered. Each one 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 event generators assume an inter-bundle creation interval time in a range (uniformly distributed) of [25, 35] seconds.

Data bundles time-to-live changes between 30, 60, 90, 120, 150, and 180 minutes, across the simulations. Increasing the TTL will lead to have more bundles stored at the nodes' buffers during longer periods of time. Therefore, more bundles can be exchanged between network nodes and this will potentially increase contention for network resources (e.g., bandwidth, buffer space). All the network nodes use a data plane link connection with a transmission data rate of 4.5 Mbps and an omni-directional transmission range of 30 meters, as considered in [275].

First Contact, Direct Delivery, Epidemic, Spray and Wait, PRoPHET, GeOpps, and GeoSpray are applied as underlying routing protocols and their performance is evaluated for each simulation scenario. In all scenarios, the configuration of PRoPHET protocol parameters is set according to the values proposed in [203] (i.e., *P_encounter* 0.75, *beta* 0.25, and *gamma* 0.999), and a GRTRMax [203] forwarding strategy is considered. Both the *source* and *binary* variants of Spray and Wait are considered. Regarding the *number of copies* parameter (*L*) of Spray and Wait and GeoSpray, [202] provides information on how to choose this value for Spray and Wait to achieve a required expected delay, or when network parameters are unknown. Since this study assumes that the total number of network nodes is known, then based on the conclusions presented in [240], *L* is equal to 15% of the mobile nodes available in the simulation scenario. Hence, for both Spray and Wait and GeoSpray, *L* has a value of 15 in the scenario with 100 vehicles, and value of 30 in the scenario with 200 vehicles.

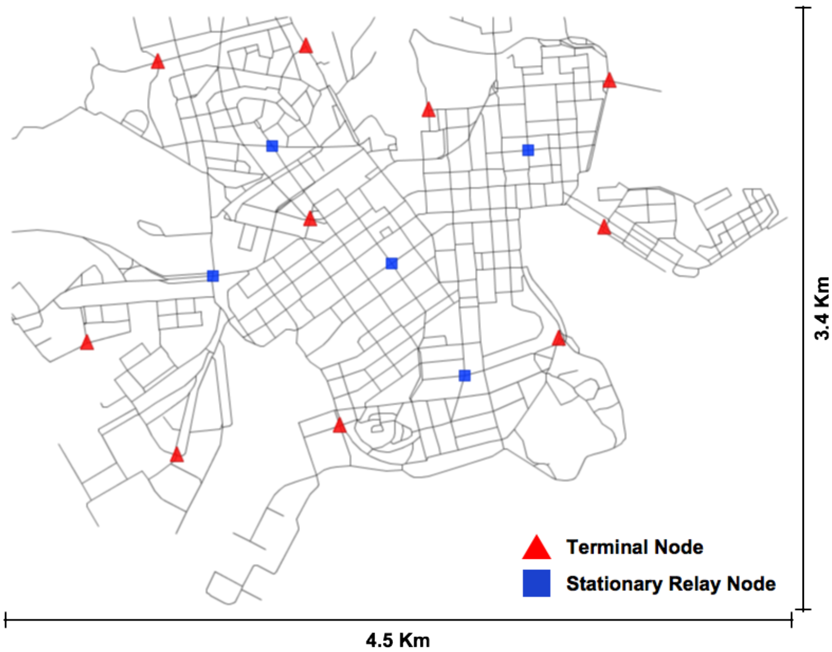

Figure 6.30: Illustration of the Helsinki downtown (Finland) map (area of 4500×3400 meters), with the locations of the terminal nodes and the stationary relay nodes.

6.7.2. Results Analysis

The performance evaluation starts with the comparison of the routing protocols in respect to the number of initiated bundle transmissions. The combined analysis of Figures 6.31 and 6.32 shows that the number of mobile nodes (i.e., vehicles) has a direct effect on the number of initiated bundle transmissions due to the increased number of contact opportunities. This observation is valid for all protocols considered in this study except Direct Delivery. In Direct Delivery routing protocol, a node waits to forward its bundle until it meets the bundle's destination node. Hence, this routing protocol presents the lowest numbers of initiated bundle transmissions across all the simulations and is not significantly affected by different numbers of mobile nodes.

Regarding the other two single-copy protocols, First Contact and GeOpps, it was observed that GeOpps initiates fewer bundle transmissions than First Contact. This is due to the fact that GeOpps uses geographic information to ensure that a bundle is forwarded only to a node that will be geographically closer to the bundle's destination, while First Contact performs a "random walk" search for the destination node.

Epidemic routing protocol registers the largest number of initiated bundle transmissions across all simulations, as expected. This is caused by its flooding approach that simply replicates bundles at contact opportunities. Furthermore, it is aggravated when bundles have larger TTLs because nodes store bundles during longer periods of time that will be replicated even more. PRoPHET's operating principle attempts to limit flooding using the history information of node encounters and transitivity. Nevertheless, in the studied scenarios, this protocol presents the second worst results in this performance metric.

The proposed protocol, referred to as GeoSpray, is inspired on the Spray and Wait Binary controlled replication strategy. Nevertheless, results show that GeoSpray initiates more transmissions than Spray and Wait. This behavior was expected because after distributing a small number of bundle copies to nodes according to geographic routing decisions, GeoSpray allows each of the nodes that received a bundle copy to further forward it to another node that goes closer or arrives sooner to the bundle's final destination. On the contrary, in Spray and Wait routing, after the "spray phase" nodes can only forward bundles if they meet the bundle's final destination (i.e., performing direct delivery). From the analysis of these figures it is also possible to observe that both GeoSpray and Spray and Wait Binary and Source variants are not significantly affected by increasing the bundles TTL.

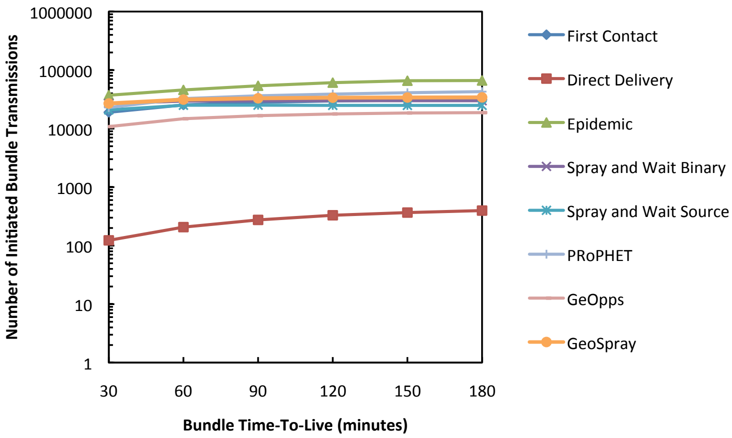

Figure 6.31: Number of initiated bundle transmissions as function of bundles TTL in a scenario with 100 vehicles for First Contact, Direct Delivery, Epidemic, Binary and Source Spray and Wait, PRoPHET, GeOpps, and GeoSpray routing protocols.

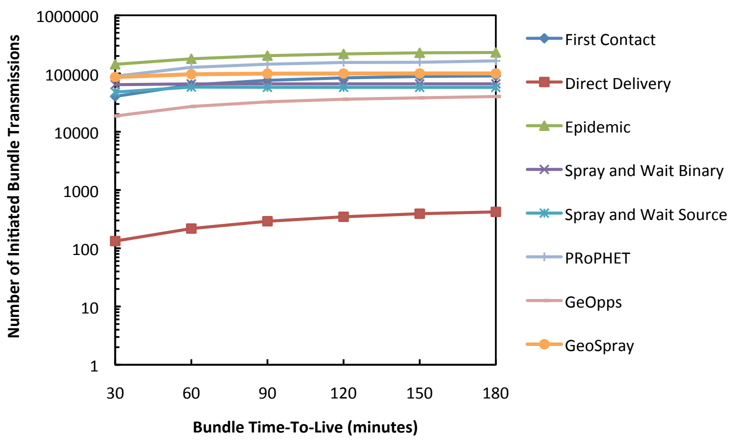

Figure 6.32: Number of initiated bundle transmissions as function of bundles TTL in a scenario with 200 vehicles for First Contact, Direct Delivery, Epidemic, Binary and Source Spray and Wait, PRoPHET, GeOpps, and GeoSpray routing protocols.

As should be expected, performing bundle replication at contact opportunities has a direct effect on the number of bundles dropped from the nodes' buffers. Single-copy (i.e., forwarding) routing protocols (First Contact, Direct Delivery, and GeOpps) maintain at most one copy of a bundle in the network, which results in low buffer utilization and hence low numbers of dropped bundles. Close observation of Figures 6.33 and 6.34 reveals that for these protocols the number of dropped bundles decreases with larger TTL values. Moreover, GeOpps presents the best results in this performance metric.

Multiple-copy routing protocols (Epidemic, Spray and Wait, PRoPHET, and GeoSpray) use different bundle replication strategies to improve the probability of delivery and minimize the delivery latency. The downside is that such strategies increase the contention for network resources like bandwidth and storage. Figures 6.33 and 6.34 show that Epidemic flooding results in severe buffer overflow and consequent high bundle drop rate. A very interesting conclusion that can be drawn from the analysis of Figures 6.31, 6.32, 6.33, and 6.34 is that although GeoSpray initiates more bundle transmissions than Spray and Wait, it presents much lower bundle drop rates. This is caused by GeoSpray's module that is responsible for explicitly clearing delivered bundles across network nodes, thus freeing essential buffer space. The difference in the number of dropped bundles between GeoSpray and the other multiple-copy protocols increases further in the scenario with 200 vehicles.

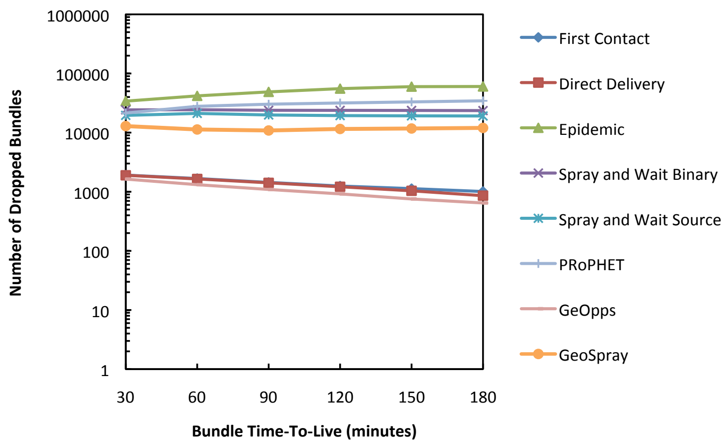

Figure 6.33: Number of dropped bundles as function of bundles TTL in a scenario with 100 vehicles for First Contact, Direct Delivery, Epidemic, Binary and Source Spray and Wait, PRoPHET, GeOpps, and GeoSpray routing protocols.

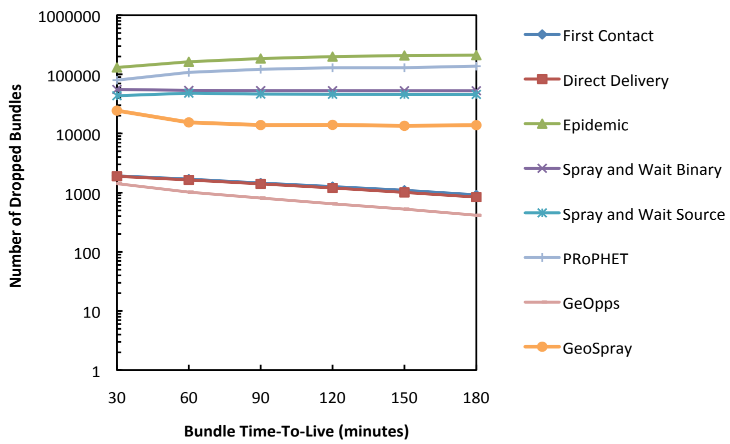

Figure 6.34: Number of dropped bundles as function of bundles TTL in a scenario with 200 vehicles for First Contact, Direct Delivery, Epidemic, Binary and Source Spray and Wait, PRoPHET, GeOpps, and GeoSpray routing protocols.

As discussed in Subsection 2.3.2, one of the main problems of single-copy routing schemes is that they suffer from low delivery ratios. Figures 6.35 and 6.36 show that First Contact and Direct Delivery perform poorly in the two scenarios considered in this study. In order to improve the routing efficiency, GeOpps uses geographic location information to make forwarding decisions. It is interesting to observe that the single-copy routing approach of GeOpps achieves higher bundle delivery probabilities than Epidemic and PRoPHET (multiple-copy protocols) for TTL values equal or greater than 60 minutes in both scenarios. Moreover, in Figure 6.36 it is possible to observe that GeOpps attains similar delivery probabilities to those of the two variants of Spray and Wait, in the scenario with 200 vehicles and TTL values equal to or greater than 120 minutes. These conclusions demonstrate the importance of using location information to make better routing decisions in VDTN networks.

The GeoSpray routing protocol, with its hybrid approach inspired in both GeOpps and Binary Spray and Wait, combines the best of these two protocols. The analysis of Figures 6.35 and 6.36 shows that GeoSpray greatly outperforms all other routing protocols in terms of bundle delivery probability. Moreover, these results show that the performance differences increase with a larger number of mobile nodes. For instance, in the scenario with 100 mobile nodes (Figure 6.35), for TTL values greater than 60 minutes, GeoSpray increases the bundle delivery probability in approximately 16% when compared to GeOpps, and in approximately 11% when compared to Binary Spray and Wait. In the scenario with 200 mobile nodes (Figure 6.36) and TTL values greater than 120 minutes GeoSpray increases the bundle delivery probability in approximately 23% when compared to GeOpps and to Spray and Wait variants.

A final observation to be made regarding these figures is that the two variants of Spray and Wait present similar delivery probabilities for TTL values equal to or greater than 90 minutes.

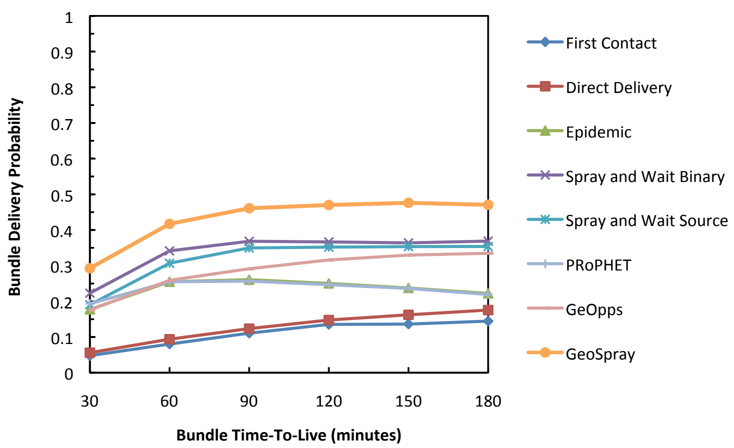

Figure 6.35: Bundle delivery probability as function of bundles TTL in a scenario with 100 vehicles for First Contact, Direct Delivery, Epidemic, Binary and Source Spray and Wait, PRoPHET, GeOpps, and GeoSpray routing protocols.

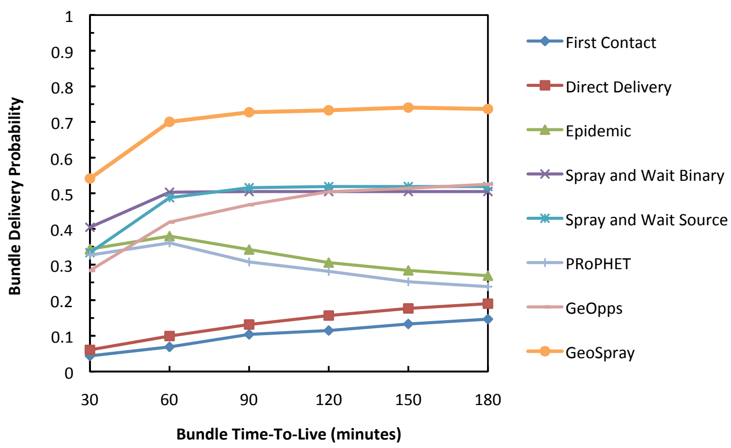

Figure 6.36: Bundle delivery probability as function of bundles TTL in a scenario with 200 vehicles for First Contact, Direct Delivery, Epidemic, Binary and Source Spray and Wait, PRoPHET, GeOpps, and GeoSpray routing protocols.

The analysis of Figures 6.35 to 6.38 reveals that, in addition to significantly improving the bundle delivery probability, GeoSpray presents low bundle average delivery delays. It can be seen from Figures 6.37 and 6.38 that Source Spray and Wait results in higher bundle average delivery delays than Binary Spray and Wait. The performance difference between these two variants increases as the number of mobile nodes increases (from 100 to 200). Furthermore, in the scenario with 200 mobile nodes, Binary Spray and Wait presents the lowest bundle average delivery delays among all protocols considered.

It would be expected that increasing the number of mobile nodes would result in reducing the bundle average delivery delay for all routing protocols (under the same traffic load). Nonetheless, it is possible to observe that First Contact, Direct Delivery and Epidemic do not benefit from a larger number of mobile nodes. These protocols provide the highest average delivery delays for TTL values equal to or greater than 120 minutes, in both studied scenarios.

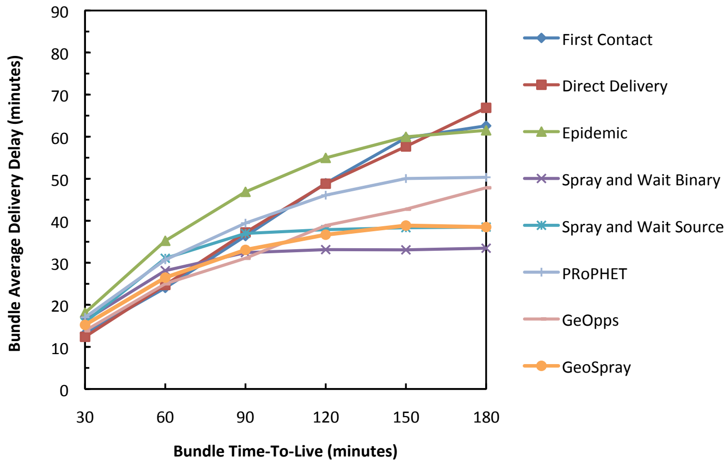

Figure 6.37: Bundle average delivery delay as function of bundles TTL in a scenario with 100 vehicles for First Contact, Direct Delivery, Epidemic, Binary and Source Spray and Wait, PRoPHET, GeOpps, and GeoSpray routing protocols.

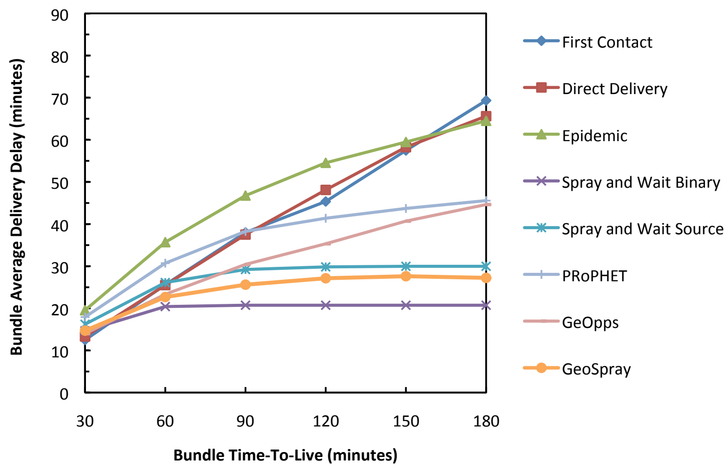

Figure 6.38: Bundle average delivery delay as function of bundles TTL in a scenario with 200 vehicles for First Contact, Direct Delivery, Epidemic, Binary and Source Spray and Wait, PRoPHET, GeOpps, and GeoSpray routing protocols.

The overhead ratio is an important and interesting performance metric. It represents the bandwidth efficiency of the routing protocols, since it measures how many bundle transfers were needed for each bundle delivery. From Figures 6.39 and 6.40, it can be seen that increasing the number of mobile nodes increases the number of contact opportunities, which naturally leads to higher overhead ratios. This conclusion is valid for all protocols, except Direct Delivery.

One can observe that Direct Delivery routing protocol does not introduce any overhead. This was expected since this single-copy routing protocol only forwards bundles directly between the source node and the destination node, thus relying entirely on node mobility. In contrast, First Contact, Epidemic, and PRoPHET present the highest overhead ratios among the protocols evaluated. It is interesting to note that the First Contact single-copy routing strategy, where a node forwards a bundle to first node encountered, presents the highest overhead in the two scenarios considered in this study, for TTL values lower than 120 minutes.

GeoSpray atains overhead ratios similar to the ones presented by Spray and Wait variants. Furthermore, in the scenario with 100 mobile nodes (Figure 6.39), GeoSpray and GeOpps present similar values of overhead ratio. This allows concluding that the proposed protocol is efficient in terms of bandwidth utilization.

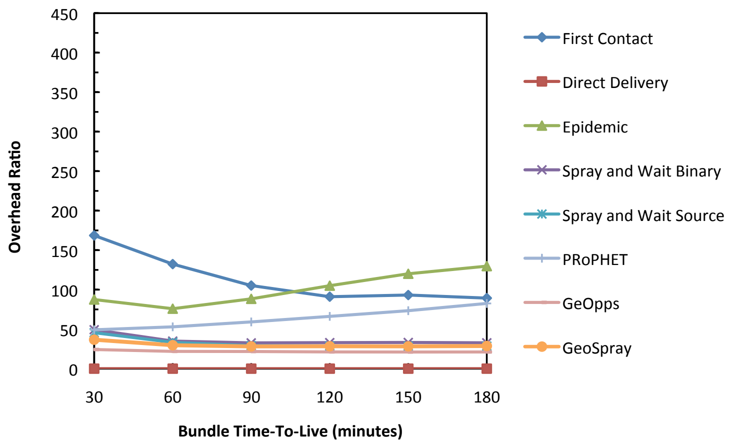

Figure 6.39: Overhead ratio as function of bundles TTL in a scenario with 100 vehicles for First Contact, Direct Delivery, Epidemic, Binary and Source Spray and Wait, PRoPHET, GeOpps, and GeoSpray routing protocols.

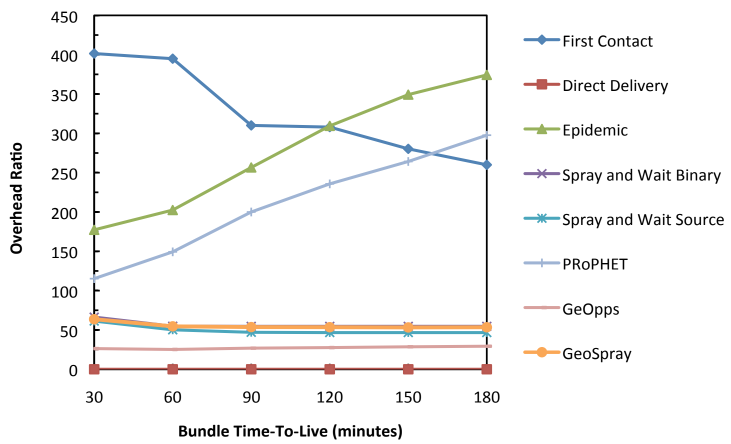

Figure 6.40: Overhead ratio as function of bundles TTL in a scenario with 200 vehicles for First Contact, Direct Delivery, Epidemic, Binary and Source Spray and Wait, PRoPHET, GeOpps, and GeoSpray routing protocols.

The analysis of the results of the average hop count shows the advantage of performing bundle replication together with routing decisions that exploit geographic location information. As can be seen from Figures 6.41 and 6.42, GeOpps registers a larger average hop count than GeoSpray due its single-copy approach. This means that, with GeOpps, a bundle needs to be relayed between more nodes to reach its destination, than with GeoSpray. The difference in the average hop count between these protocols increases significantly in the scenario with 200 mobile nodes (Figure 6.42). As expected, Direct Delivery requires a single hop to deliver data and First Contact presents the worst results in this performance metric, irrespective of the scenario.

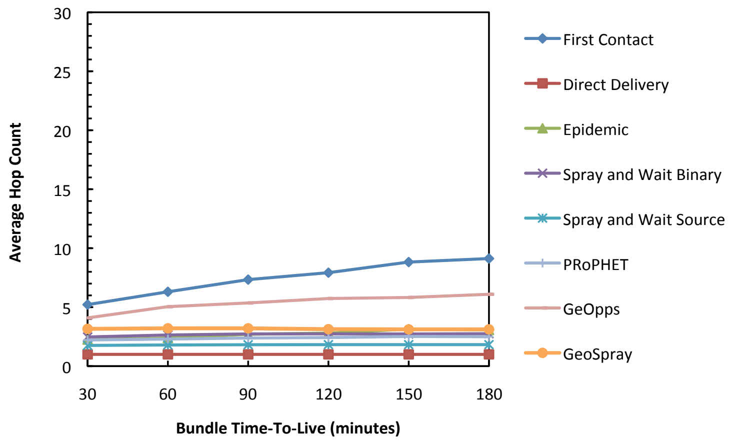

Figure 6.41: Average hop count as function of bundles TTL in a scenario with 100 vehicles for First Contact, Direct Delivery, Epidemic, Binary and Source Spray and Wait, PRoPHET, GeOpps, and GeoSpray routing protocols.

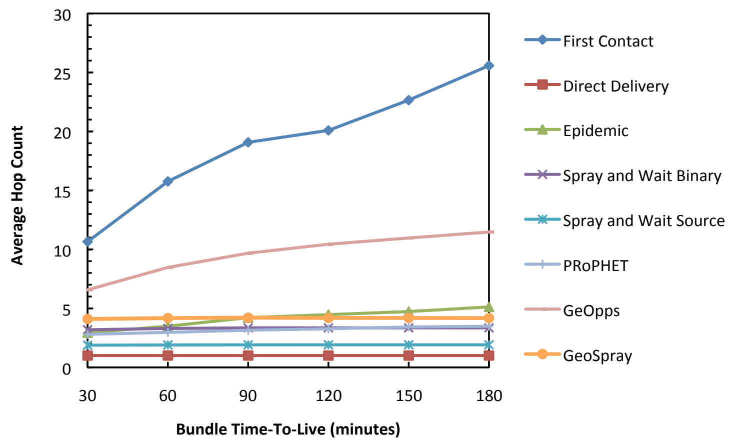

Figure 6.42: Average hop count as function of bundles TTL in a scenario with 200 vehicles for First Contact, Direct Delivery, Epidemic, Binary and Source Spray and Wait, PRoPHET, GeOpps, and GeoSpray routing protocols.

The last performance metric considered to evaluate the behavior of the routing protocols is the average buffer time. This metric represents the average time that bundles stay in the nodes' buffers, from creating/receiving them until they are dropped or removed. The analysis of the results shown in Figures 6.43 and 6.44 demonstrates that the operating principle of Direct Delivery leads to long average buffer times. In contrast, the other two single-copy protocols (First Contact and GeOpps) present short buffer times because, when these protocols are used, nodes forward bundles to intermediate nodes and remove them from their buffers.

In both studied scenarios, GeoSpray presents shorter average buffer times than Spray and Wait variants. This behavior is due to the active receipts used by GeoSpray to clear delivered bundles across the network nodes, in order to improve storage and bandwidth resources utilization.

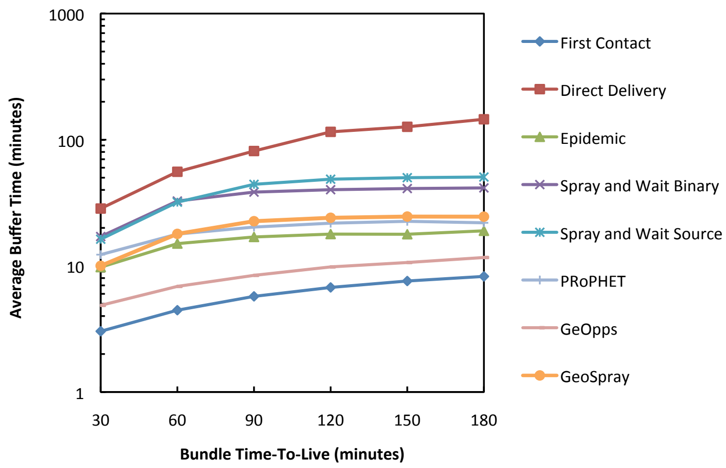

Figure 6.43: Average buffer time as function of bundles TTL in a scenario with 100 vehicles for First Contact, Direct Delivery, Epidemic, Binary and Source Spray and Wait, PRoPHET, GeOpps, and GeoSpray routing protocols.

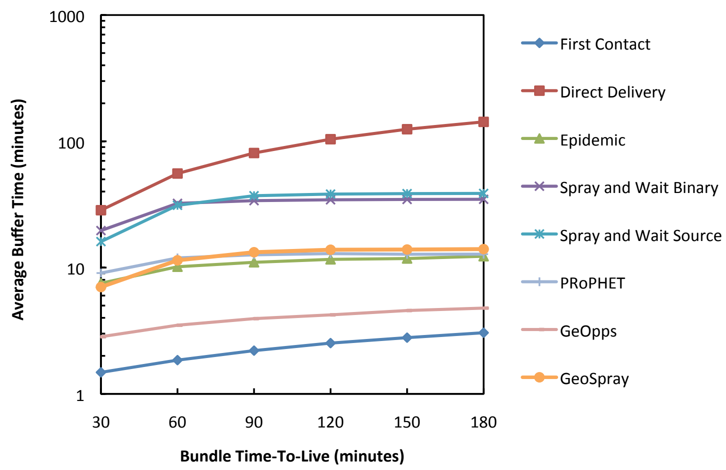

Figure 6.44: Average buffer time as function of bundles TTL in a scenario with 200 vehicles for First Contact, Direct Delivery, Epidemic, Binary and Source Spray and Wait, PRoPHET, GeOpps, and GeoSpray routing protocols.

6.8. Testbed-based Performance Evaluation of Routing Protocols

This Section presents a study carried out in the VDTN@Lab testbed presented in Section 4.3. The testbed was used to demonstrate VDTN networks and to conduct experiments for performance evaluation of five well-known DTN routing protocols (First Contact [194], Direct Delivery [196], Epidemic [200], Source Spray and Wait [202], and PRoPHET [203]) presented in Subsection 2.3.2, applied to VDTNs. Performance metrics considered in this study include the bundle delivery probability, the bundle average delivery delay, and the number of dropped bundles.

6.8.1. Experimental Setup

The scenario that was set up to conduct experiments on the VDTN testbed has a dimension of 36.5 m^2 and is shown in Figure 6.45. It considers three terminal nodes, two relay nodes, and four mobile nodes. Terminal nodes are placed at different points of the laboratory. Stationary relay nodes are placed on road intersections. Mobile nodes follow a random movement along the road topology at different speeds. Mobile node 1 moves at 0.96 km/h, mobile node 2 at 0.72 km/h, mobile node 3 at 0.58 km/h, and mobile node 4 at 0.48 km/h. The nodes' buffers have different capacities according to their roles in the network. Terminal nodes have a buffer with a 50 MB of capacity, relay nodes 75 MB, and mobile nodes 25 MB. These buffers are managed according to a FIFO ("drop head") policy.

Data bundles are generated with a time interval of 20 seconds at random mobile nodes and are destined to random terminal nodes. Two different scenarios are considered in this study. In the first one (Scenario 1), the bundles' TTL is fixed to 20 minutes and their size changes between 128, 256, 512, 1024, and 2048 KB across all the experiments. In Scenario 2, the bundles' TTL changes between 5, 10, 15, and 20 minutes across all the experiments. In this scenario, the bundles' size is uniformly distributed between 256 KB and 2 MB. Each testbed experiment runs during an hour and it is assumed a fully cooperative opportunistic environment.

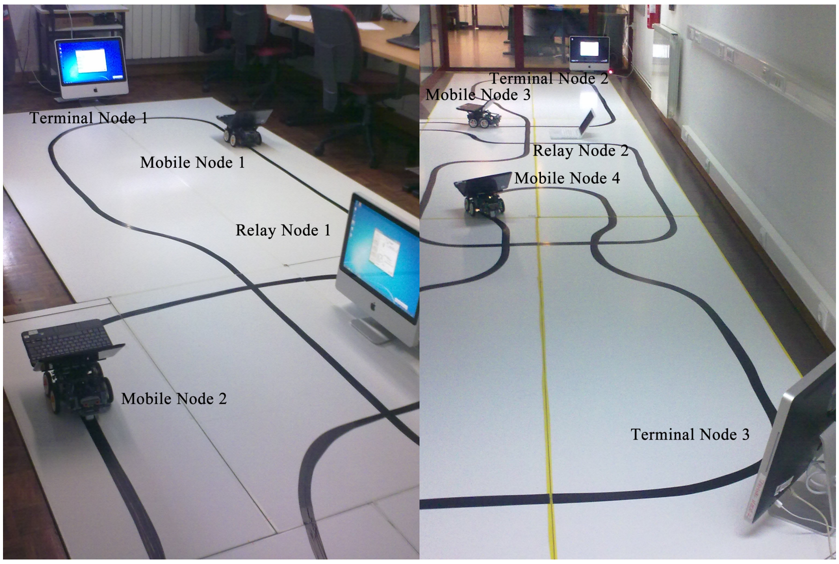

Figure 6.45: Photos of the VDTN@Lab testbed under experiments.

6.8.2. Experimental Results

Scenario 1

This study starts with the analysis of the effect of the bundle size on the performance of the different routing protocols. Due to the limited bandwidth and short contact duration, only a limited number of bundles can be transferred at a contact opportunity. Hence, as may be seen in Figure 6.46, the bundle size has a direct influence on the bundle delivery probability of all routing protocols. The bundle delivery probability decreases for large bundle sizes.

As may be seen, multiple-copy routing protocols present higher delivery probabilities in comparison with single-copy protocols. In particular, Spray and Wait presents the best results across all the experiments. It improves the bundle delivery probability approximately in 3%, 7%, 6%, 12%, and 8% (for each of the considered values of bundles size) when compared to Epidemic, and 22%, 28%, 32%, 35%, and 28% when compared to PRoPHET. The performance differences between Spray and Wait and Epidemic would be more pronounced with more restrictions on bandwidth and storage space. The performance of PRoPHET routing protocol is affected by the scenario under study, namely because of the limited number of network nodes and the mobility pattern of mobile nodes.

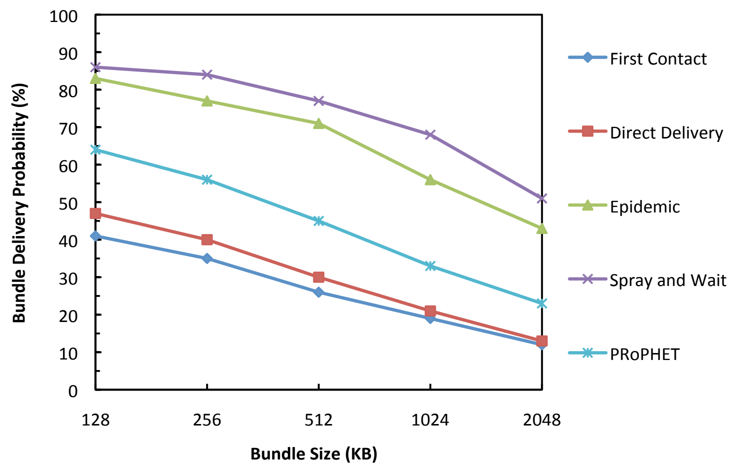

Figure 6.46: Bundle delivery probability as function of bundles size for First Contact, Direct Delivery, Epidemic, Spray and Wait, and PRoPHET routing protocols.

Figure 6.47 shows that, besides improving the bundle delivery probability, Spray and Wait also presents the lowest bundle average delivery delays. When compared to Epidemic, bundles arrive to the destination approximately 16, 18, 66, 98, and 175 seconds sooner in average, and approximately 69, 76, 114, 145, and 215 seconds sooner when compared to PRoPHET.

In Figure 6.47 it is also possible to observe that single-copy routing schemes suffer from longer average delivery delays. For example, when Spray and Wait is compared with Direct Delivery, bundles arrive at the destination approximately 108, 116, 136, 185, and 268 seconds sooner on average. As a final note to Figures 6.46 and 6.47, it can be seen that higher bundle delivery probabilities and smaller bundle average delivery delays are obtained for smaller bundle sizes (for all routing protocols).

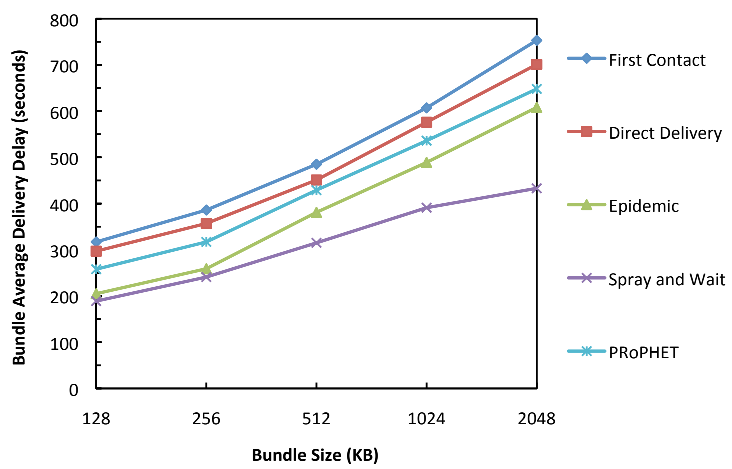

Figure 6.47: Bundle average delivery delay as function of bundles size for First Contact, Direct Delivery, Epidemic, Spray and Wait, and PRoPHET routing protocols.

Figure 6.48 displays the results regarding the number of dropped bundles. As expected, increasing the bundles' size creates contention for buffer space and consequently leads to bundle drops. Due to its pure flooding scheme, Epidemic presents the worst results in this performance metric. Spray and Wait succeeds in limiting replication by setting an upper bound on the number of replicas created per bundle, thus saving network resources (e.g., bandwidth and storage). Since single-copy routing strategies maintain only one copy of each bundle in the network, First Contact and Direct Delivery routing protocols register the lowest numbers of dropped bundles.

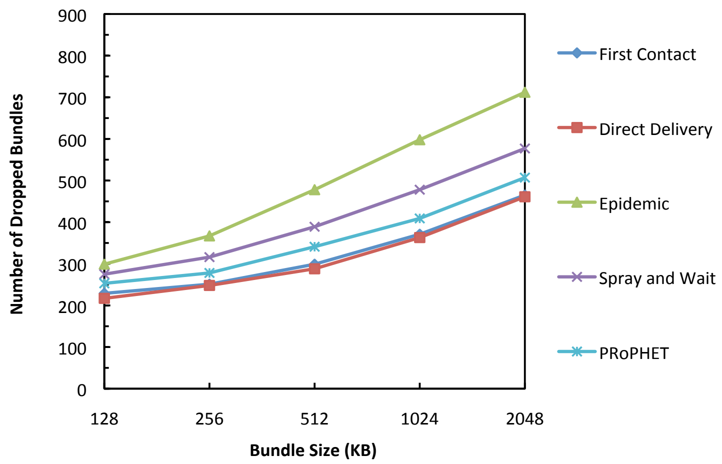

Figure 6.48: Number of dropped bundles as function of bundles size for First Contact, Direct Delivery, Epidemic, Spray and Wait, and PRoPHET routing protocols.

Scenario 2

The second scenario evaluates how the performance of these routing protocols is affected by the bundles' TTL value. Intuitively, increasing the TTL value leads to have more bundles stored in the network nodes' buffers during longer periods of time. As may be observed in Figure 6.49, this increases the probability of bundle delivery for all the considered routing protocols. Following the previous scenario, the results depicted in this figure confirm that Spray and Wait routing protocol performs better than the other protocols analyzed in this study. Compared to Epidemic, Spray and Wait increases the bundle delivery probability in about 14%, 8%, 10%, and 9% for each of the considered values of TTL, respectively. When compared to PRoPHET, it presents gains of 22%, 21%, 22%, and 19% in this performance metric.

Direct Delivery and First Contact single-copy routing strategies have the worst delivery probabilities again, for the same reasons stated in the previous scenario. Maintaining a single copy of each bundle results in frequently dropping bundles due to TTL expiration, before they arrive at the destination terminal node. This figure shows that Direct Delivery performs better than First Contact. Nevertheless, it is interesting to observe that compared to First Contact, Spray and Wait increases the bundle delivery probability in 41%, 45%, 44%, and 41%.

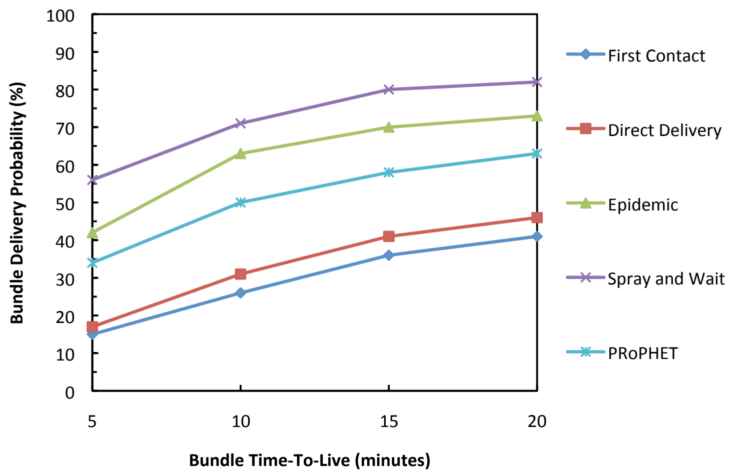

Figure 6.49: Bundle delivery probability as function of bundles TTL for First Contact, Direct Delivery, Epidemic, Spray and Wait, and PRoPHET routing protocols.

From the combined analysis of Figures 6.49 and 6.50, it is possible to observe that increasing the bundles' TLL leads to higher bundle delivery probabilities but also to longer bundle average delivery delays. Again, the Spray and Wait routing protocol provides lower bundle delivery delays for all the considered TTL values. Note that the bundle average delivery delay difference between this protocol and the other considered protocols increases with larger TTLs. In this scenario, Spray and Wait decreases the bundle average delivery delay in approximately 13, 70, 149, and 233 seconds when compared to Epidemic, and in 98, 199, 300, and 404 seconds compared to First Contact.

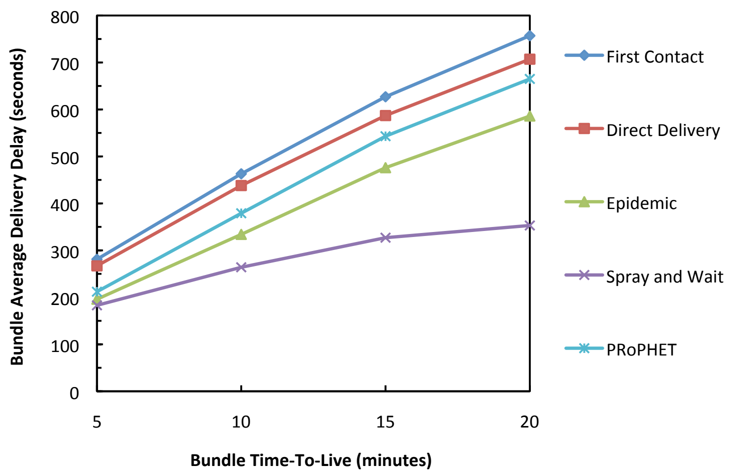

Figure 6.50: Bundle average delivery delay as function of bundles TTL for First Contact, Direct Delivery, Epidemic, Spray and Wait, and PRoPHET routing protocols.

Figure 6.51 shows that single-copy and multiple-copy routing protocols have different behaviors with respect to the number of dropped bundles. For single-copy protocols, increasing the bundles' TTL resulted in decreasing the number of dropped bundles. On the contrary, for multiple-copy protocols increasing the bundles' TTL leads to more bundle replications that take up more storage space and increase the number of dropped bundles. This figure also confirms the conclusions obtained in the first scenario. Direct Delivery registers the lowest numbers of dropped bundles across the experiments and Epidemic presents the worst results in this performance metric.

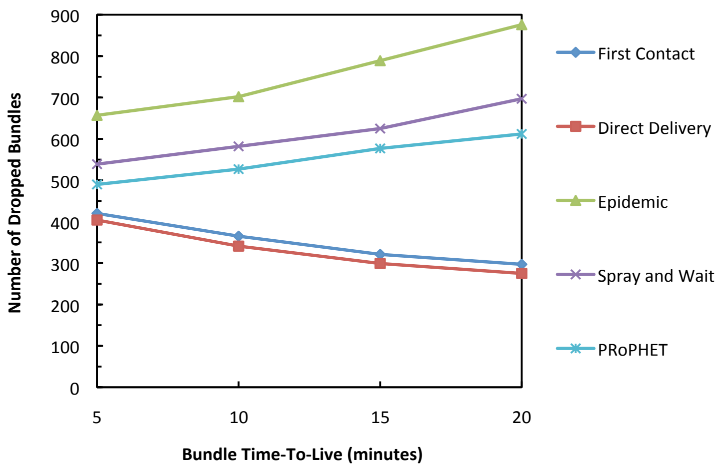

Figure 6.51: Number of dropped bundles as function of bundles TTL for First Contact, Direct Delivery, Epidemic, Spray and Wait, and PRoPHET routing protocols.

6.9. Summary

This Chapter discussed a number of issues that influence the performance of VDTN networks, namely, node localization, cooperation, queueing disciplines, traffic differentiation, and routing. First, Section 6.2 described the performance metrics under consideration in the simulation and testbed studies presented in this Chapter.

Section 6.3 presented a simulation study to observe the effects of using the function of node localization presented in Section 3.3. It was shown that contact duration prediction allows preventing incomplete bundle transmissions, thus optimizing data plane link utilization. This function performed at the control plane has a significant effect on improving the bundle delivery probability and the bundle average delivery delay. Moreover, it contributes to extend the battery life of power-limited network nodes, like stationary relay nodes.

In Section 6.4, the effect of node cooperation on routing protocols performance was evaluated. Like in other DTN-based networks, VDTNs rely on cooperation behavior to help delivering bundles across sporadically connected nodes. Network nodes should share their constrained storage, bandwidth, and eventually energy resources (e.g., stationary relay nodes) with one another. Thus, each node should contribute to store, carry, and forward network data, to mutually enhance the overall network performance. However, the nodes may decide to not cooperate, for instance either due to selfish or malicious behavior. This severely affects the network functionality. The simulation studies conducted in this research focused on evaluating the impact of node cooperation at the data plane level. It was shown that non-cooperative behavior severely affects the bundle delivery probability and the bundle average delivery delay on Epidemic and Spray and Wait routing protocols, with a more pronounced effect on the last one. This study is helpful for understanding the implications of cooperation, and reinforces the need for developing an incentive mechanism that can act as a basis for achieving cooperation between network nodes.

Section 6.5 revisited the problems caused by the combination of bundle storage during long periods of time and their replication, which lead to high storage and bandwidth overhead. Since VDTN networks are resource-constrained, a key challenge is to provide scheduling and dropping policies that can contribute to improve the network performance. In this context, this Section addressed the impact of different combinations of scheduling and dropping policies over the bundle delivery probability and the bundle average delivery delay. The results revealed a good performance obtained by a combination of a scheduling policy and a dropping policy that gives preferential treatment to less replicated bundles. It has been shown that such approach outperforms the commonly used FIFO scheduling with “drop head” buffer management/discard policy, in both performance metrics.

Section 6.6 has evaluated the efficiency and tradeoffs of the proposals for implementing traffic prioritization on VDTN networks, presented in Section 3.4. The results confirmed the importance of supporting traffic differentiation on VDTNs, and motivate further research in this domain to develop new proposals for prioritization scheduling policies. Furthermore, introducing “quality of service” routing capabilities and studying its effect over the network traffic and the network utilization are also open research issues that may be addressed in future works.

In Section 6.7, the performance assessment of the proposed GeoSpray routing protocol (presented in Section 3.5) was discussed. GeoSpray combines a store-carry-and-forward paradigm with routing decisions based on geographical location information. GeoSpray presents a hybrid approach combining multiple-copy and single-copy routing schemes. First, it starts with a multiple-copy scheme, which spreads a limited number of bundle copies in order to exploit alternative paths. Then, it switches to a forwarding (single-copy) scheme, which takes advantage of additional contact opportunities to improve the bundle delivery probability and reduce the bundle average delivery delay. In order to further improve resources utilization, the protocol applies the concept of active receipts to clear delivered bundles across the network nodes.

The performance of GeoSpray was evaluated in comparison with the well-known geographic location based single-copy (GeOpps), non-location based single-copy (First Contact, Direct Delivery), and multiple-copy routing protocols (Epidemic, Spray and Wait, and PRoPHET). The following performance metrics were considered: bundle delivery probability, bundle average delivery delay, number of initiated bundle transmissions, number of dropped bundles, overhead ratio, average hop count, and average buffer time. It was shown that GeoSpray protocol significantly improves the bundle delivery probability and reduces the bundle delivery delay, compared to the other single-copy and multiple-copy routing protocols under evaluation. Furthermore, it presents a much lower rate of dropped bundles than other multiple-copy routing protocols. Moreover, GeoSpray also has a low overhead ratio. Therefore, it was demonstrated that this protocol is efficient in terms of storage and bandwidth resources utilization.

The last Section 6.8, presented the results from a study conducted through the VDTN@Lab testbed that evaluates the performance of First Contact, Direct Delivery, Epidemic, Spray and Wait, and PRoPHET routing protocols applied to VDTN networks. It was observed that First Contact and Direct Delivery single-copy routing approaches reduce the buffer and bandwidth usage but suffer from long bundle average delivery delay and low bundle delivery probability. Epidemic, Spray and Wait, and PRoPHET multiple-copy schemes improve these performance metrics. Furthermore, it was concluded that Spray and Wait presents the best performance results. It consumes fewer network resources than unconstrained Epidemic flooding, while improves the bundle delivery probability and reduces the bundle average delivery delay. The performance of PRoPHET protocol was affected by the scenario under study, namely because of the limited number of network nodes and the mobility pattern of mobile nodes. These results corroborate and validate previous conclusions from studies performed through simulation that were presented in the previous Sections.

Chapter 7

Conclusions and Future Work

7.1. Conclusions

Throughout this thesis, the performance of vehicular delay-tolerant networks was studied. This Chapter presents a synthesis of the main achievements and provides directions for future work.

After introducing and delimiting the theme of the thesis, describing the objectives, and presenting its main contributions, in Chapter 2, the state of the art related to vehicular networks and delay-tolerant networks was reviewed. This Chapter began with an overview of the applications of vehicular networks and the research projects related to these networks. After, vehicular ad hoc network architecture was presented. Special attention was devoted to discuss the limitations of the traditional routing and data dissemination strategies proposed for VANETs. These limitations have motivated the introduction of concepts derived from delay-tolerant networks in VANETs. Concerning DTNs, the proposed architecture for these networks was described. Several research topics in DTNs were also introduced and discussed, namely, application scenarios, routing protocols, stationary relay nodes, cooperation, and queuing disciplines.

Chapter 3 presented the proposal of a new layered architecture for vehicular communications in sparse or partitioned opportunistic vehicular networks, called vehicular delay-tolerant network. VDTN architecture is based on the store-carry-and-forward paradigm of delay-tolerant networks. Its distinctive features come from the introduction of an IP over VDTN approach combined with control plane and data plane separation, performing out-of-band signaling. The main idea of VDTN architecture is to assemble IP packets into variable length data bundles, and transmit/route these DBs asynchronously through the network, using the data plane. The data plane connection is set up using out-of-band signaling information previously transmitted through a separate control plane connection. The VDTN architecture layers were identified and defined, and the features of the protocols that are likely to reside in each layer were described and discussed.

Next, the characteristics of control plane and data plane separation with out-of-band signaling were explored to introduce the function of node localization at the control plane. It was discussed how this functionality can be used to predict the contact durations and the maximum number of bytes that can be transmitted during contact opportunities. Moreover, it was shown how knowing the contact duration, makes it possible to determine the period of time during which the data plane link should be activated, and thus extend the battery life of power-limited nodes, such as stationary relay nodes.

After, the implementation of traffic differentiation in VDTN networks was considered. A priority classes of service model was assumed. It was analyzed how different buffer management strategies, dropping and scheduling policies, can provide strict priority based services or custom allocation of network resources.

Concerning routing in VDTNs, a new geographic routing protocol, called GeoSpray, was proposed. GeoSpray is based on the following design principles: *i)* supporting an opportunistic networking paradigm and the delivery of bundles based on the store-carry-and-forward paradigm; *ii)* using geographical location information provided by positioning devices to assist in routing decisions; *iii)* employing a multiple-copy routing scheme, with a strict upper bound on the number of copies per bundle, combined with a forwarding routing strategy, to improve the timely delivery of bundles across multi-hop routes; *iv)* clearing bundles that have already been delivered to the destinations; *v)* optimizing the resources used in the network, including storage, bandwidth, and energy; and *vi)* maximizing the bundle delivery probability, minimizing the bundle delivery delay and overhead.

Taking into account the particularities of VDTN network architecture, a new simulation tool was created to support performance studies related with the development, experimentation, and performance evaluation of protocols, algorithms, services, and applications. This simulation tool, called VDTNsim, was presented in Chapter 4. VDTNsim was used to support the simulation studies presented in Chapters 5 and 6. Chapter 4 also described a prototype of a laboratory testbed for VDTN networks called VDTN@Lab. This testbed intends to demonstrate the use of VDTNs, offering the support for performance evaluation and validation of protocols, algorithms, services, and applications for these networks, as well as for validation of simulation models. VDTN@Lab was used to perform studies presented in Chapter 6.

Chapter 5 initally presented a collection of projects that have used the DTN concepts and techniques to enable non real-time data exchange in opportunistic rural connectivity scenarios. Then, it was shown an example of how a VDTN network can be used in such a scenario and simulation experiments were conducted in it. Epidemic, Spray and Wait, MaxProp, and PRoPHET were used as the routing protocols for VDTN networks. The first objective of this Chapter was to evaluate the impact of stationary relay nodes when deployed in scenarios characterized by large dimensions, low mobile node density, and few contact opportunities. It was demonstrated that even in opportunistic scenarios these nodes have an essential role in the network performance. This is because they increase the number of contact opportunities, and thus contribute to significantly improve the bundle delivery probability and the bundle average delivery delay in all studied routing protocols, with a slightly more pronounced effect on MaxProp.

The second objective of this Chapter was to analyze the influence of mobile node density and mobile node movement models on the number of contact opportunities, and thus on the bundle delivery probability and the bundle average delivery delay for Epidemic, Spray and Wait, MaxProp, and PRoPHET routing protocols. Furthermore, the effect of the parameters of Spray and Wait and PRoPHET protocols was evaluated. The third and final objective of this Chapter was to study the impact caused by introducing storage capacity constraints in different network nodes, in the bundle delivery probability of the same routing protocols. It was observed that different replication strategies react in a different way to the increase of the buffer size in specific network nodes. For example, Epidemic and MaxProp protocols benefit from increased storage capacity in all network nodes, while Spray and Wait only improves the bundle delivery probability if the mobile nodes storage capacity is increased.

Chapter 6 addressed several important techniques for improving the performance of vehicular delay-tolerant networks. The first objective of this Chapter was to analyze the impact of the function of node localization on the overall network performance. The results of the reported studies show that predicting the contact durations allows preventing incomplete bundle transmissions, thus increasing the number of successfully relayed bundles. The optimization of data plane link utilization resulted in improving the bundle delivery probability and the bundle average delivery delay considerably.

The second objective of this Chapter was to analyze how the lack of node cooperation can affect the network performance. The studies focused on evaluating the impact of node cooperation at the data plane level of VDTNs. From the analysis of the results, it was made clear that non-cooperative behavior severely affects the bundle delivery probability and the bundle average delivery delay on Epidemic and Spray and Wait routing protocols, with a more pronounced effect on the last one. This study paves the way for further research on mechanisms for incentivizing cooperation between network nodes.

The third objective of this Chapter was to study the network performance implications of different scheduling policies and dropping policies on the bundle delivery probability and the bundle average delivery delay. From this analysis, it was concluded the importance of using a combination of a scheduling and a dropping policy that gives preferential treatment to less replicated bundles. It was observed that such a combination performs much better than the traditional head-drop FIFO queue, in both performance metrics.

The fourth objective of this Chapter was to analyze the performance of the proposed traffic differentiation mechanisms at the VDTN layer. Buffer management strategies and dropping policies with distinct approaches to buffer space allocation and contention resolution were combined with scheduling policies with different solutions to the traffic prioritization problem. A performance evaluation of these proposals was presented. The results confirmed the importance of supporting traffic differentiation on VDTNs and motivate further research in this topic.

The fifth objective of this Chapter was to evaluate the performance of GeoSpray in comparison with First Contact, Direct Delivery, Epidemic, Binary and Source Spray and Wait, PRoPHET, and GeOpps, which are popular DTN routing protocols. The performance metrics considered in this study were the bundle delivery probability, the bundle average delivery delay, the number of initiated bundle transmissions, the number of dropped bundles, the overhead ratio, the average hop count, and the average buffer time. The routing protocols were evaluated in scenarios with different node densities. It was observed that GeoSpray significantly improves the bundle delivery probability and reduces the bundle average delivery delay, compared to the other studied routing protocols. Furthermore, it presents a low rate of dropped bundles and a low overhead ratio. Thus, the proposed protocol is also considered efficient in terms of storage and bandwidth resources utilization. It is worth to notice that GeoSpray is not exclusive to VDTN networks. Its operation principles can be applied to a variety of DTN environments.

The sixth and final objective of this Chapter was to present a testbed-based study of single-copy and multiple-copy routing protocols for VDTNs. Experiments were conducted in the VDTN@Lab testbed to evaluate the performance of First Contact, Direct Delivery, Epidemic, Spray and Wait, and PRoPHET routing protocols, under different traffic conditions. The performance metrics considered in this study were the bundle delivery probability, the bundle average delivery delay, and the number of dropped bundles. It was observed that Spray and Wait routing protocol outperforms all other protocols considered in this study, which confirms what was observed in the simulation studies presented in this thesis.

The main objective of this thesis was to present a performance study of vehicular delay-tolerant networks. Its main contribution was the proposal of a new overlay network architecture for vehicular communications, called VDTN. A performance study of several key aspects that influence the performance of VDTN networks was conducted by simulation using a tool called VDTNsim and by experimental analysis using a laboratory testbed named VDTN@Lab, which were developed in the context of this work. Various performance metrics proposed in the literature were considered. First, series of studies were conducted focusing on the impact of stationary relay nodes, mobile nodes density and movement models, and storage constraints in rural connectivity scenarios. Then, it was studied the influence of node localization, cooperation, queuing disciplines, and traffic differentiation techniques on the performance of VDTN networks. These objectives were successfully accomplished. Furthermore, as another result of this research, a new routing protocol for VDTN networks, called GeoSpray, was proposed. Overall, the findings presented in this thesis provide a number of contributions that are believed to be relevant to the development of future vehicular networks.

7.2. Future Work

To conclude this thesis, it remains to suggest future research directions that result from this research work:

- To propose, implement, and evaluate incentive mechanisms for achieving cooperation on VDTN networks.
- To introduce “quality of service” routing extensions to the GeoSpray protocol, and study its effect over the network traffic and the network resources utilization.
- To study, implement, and evaluate bundle assembly algorithms.
- To study, implement, and evaluate flow control and congestion algorithms.
- To study the effect of proactive and reactive fragmentation approaches on the performance of the routing protocols for VDTNs.
- To extend the VDTN@Lab laboratory testbed with more functionalities.
- To implement and evaluate the proposals presented in this thesis in the laboratory testbed, to compare with the simulation results.
- To create a real-world testbed for real deployment, demonstration and performance evaluation of VDTN protocols, algorithms, services, and applications. It will corroborate the results already obtained by simulation and through the laboratory testbed. An effort to pursue this objective has been already initiated with the presentation of a real testbed that demonstrates and validates the technical concepts of the VDTN architecture in a real environment [57].

Finally, it is also intended to make the VDTNsim simulation tool, the map-based model of the *Serra da Estrela* region, and the software running on the VDTN@Lab testbed available to the scientific community through the NetGNA website [58].

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