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Performance Assessment of Mobility Solutions for IPv6-based Healthcare Wireless Sensor Networks

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Foreword

This thesis describes the research work performed during the 4-year doctoral research programme and the main contributions and conclusions achieved are presented. This doctoral programme was inserted in an inter-institutional cooperation program of PhD co-supervision promoted by the Portuguese *Conselho de Reitores das Universidades Portuguesas* (CRUP) the French *Conférence des Présidents d'Université* (CPU) denoted as Luso-French Program of Integrated University Actions (PAUILF 2010) – Action No. F-CT-10/10. The PAUILF was signed between University of Beira Interior, Covilhã, Portugal and University of Haute Alsace, Colmar, France. The research work was supervised by Prof. Dr. Joel Rodrigues, from the University of Beira Interior, Covilhã, Portugal and co-supervised by Prof. Dr. Pascal Lorenz, from the University of *Haute Alsace*, *Colmar*, France. The doctoral research programme was carried in the Next Generation Networks and Applications Group (NetGNA) of the *Instituto de Telecomunicações* at the University of Beira Interior, Covilhã, Portugal. Within the scope of the 4-year doctoral programme several visits periods were made to the University of *Haute Alsace*, *Colmar*, France in order to discuss the evolution of the research work. The research programme was also partially funded by the National Funding from FCT – *Fundação para a Ciência e Tecnologia* through the Pest-OE/EEI/LA0008/2011 and Pest-OE/EEI/LA0008/2013, and AAL4ALL (Ambient Assisted Living for All (http://www.aal4all.org)) project co-funded by COMPETE (*Programa Operacional Factores de Competitividade*) under FEDER via QREN Programme. Polytechnic Institute of Castelo Branco also partially funded this doctoral research programme through an internal funding program.

List of Publications

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

1. **Intra-Mobility Support Solutions over Healthcare Wireless Sensor Networks - Handover Issues**
   João M. L. P. Caldeira, Joel J. P. C. Rodrigues, and Pascal Lorenz
   IEEE Sensors Journal, IEEE Sensors Council, vol. 13, issue 11, November, pp. 4339-4348, 2013.
   DOI: dx.doi.org/10.1109/JSEN.2013.2267729

2. **A New Wireless Biosensor for Intra-Vaginal Temperature Monitoring**
   João M. L. P. Caldeira, Joel J. P. C. Rodrigues, João F. R. Garcia, and Isabel d.l. Torre
   Sensors, MDPI, vol. 10, issue 11, November 17, pp. 10314-10327, 2010.
   DOI: dx.doi.org/10.3390/s101110314

3. **Toward Ubiquitous Mobility Solutions for Body Sensor Networks on HealthCare**
   João M. L. P. Caldeira, Joel J. P. C. Rodrigues, and Pascal Lorenz
   IEEE Communications Magazine, IEEE Communications Society, vol. 50, issue 5, May, pp. 108-115, 2012.
   DOI: dx.doi.org/10.1109/MCOM.2012.6194390

4. **MAC Layer Handover Mechanism for Continuous Communication Support in Healthcare Mobile Wireless Sensor Networks**
   João M. L. P. Caldeira, Joel J. P. C. Rodrigues, and Pascal Lorenz
   Telecommunications Systems, Springer, in press, 2013.

5. **Impact of Sensor Nodes Scaling and Velocity on Handover Mechanisms for Healthcare Wireless Sensor Networks with Mobility Support**
   João M. L. P. Caldeira, Joel J. P. C. Rodrigues, Pascal Lorenz, and Sana Ullah
   Revised version submitted for publication in an international journal, 2013.

6. **Performance Assessment of a New Intra-Mobility Solution for Healthcare Wireless Sensor Networks**
   João M. L. P. Caldeira, Joel J. P. C. Rodrigues, Marc Gilg, and Pascal Lorenz
   International Journal of Ad Hoc and Ubiquitous Computing, Inderscience, vol. 15, issue 1, March 20, pp. 215-226, 2014.
   DOI: dx.doi.org/10.1504/IJAHUC.2014.059903

Other publications resulting from this doctoral research programme not included in the thesis

1. **Intra-Mobility Handover Enhancement in Healthcare Wireless Sensor Networks**
   João M. L. P. Caldeira, Joel J. P. C. Rodrigues, Pascal Lorenz, and Lei Shu
   IEEE 14th International Conference on e-Health Networking, Applications and Services (IEEE HEALTHCOM 2012), Beijing, China, October 10-13, 2012, pp. 261-266.

2. **Mobile multimedia in Wireless Sensor Networks**
   Ricardo Silva, Jorge Sá Silva, João M. L. P. Caldeira and Joel J. P. C. Rodrigues
   International Journal of Sensor Networks (IJSNet) - Special Issue on Multimedia Data Applications in Wireless Sensor Networks, vol. 11, issue 1, 2012, pp. 3-9.
   DOI: dx.doi.org/10.1504/IJSNET.2012.045035

3. **Body Sensor Network Mobile Solutions for Biofeedback Monitoring**
   Orlando Pereira, João M. L. P. Caldeira, Joel J. P. C. Rodrigues
   Mobile Networks and Applications (MONET) (Springer) - Special Issue on Wireless and Personal Communications, vol. 16, no. 6, 2011, pp. 713-732.
   DOI: dx.doi.org/10.1007/s11036-010-0278-y

4. **Wireless Body Sensor Design for Intra-Vaginal Temperature Monitoring**
   João F. R. Garcia, João M. L. P. Caldeira, and Joel J. P. C. Rodrigues
   Fifth International Conference on Body Area Networks (BodyNets 2010), Corfu Island, Greece, September 10-12, 2010.

5. **A Symbian-based Mobile Solution for Intra-Body Temperature Monitoring**
   Orlando R. E. Pereira, João M. L. P. Caldeira, and Joel J. P. C. Rodrigues
   IEEE 12th International Conference on E-Health Networking, Applications and Services (IEEE HEALTHCOM 2010), Lyon, France, July 01-03, 2010. (**Received the Best Paper Award**)

6. **Intra-Body Temperature Monitoring using a Biofeedback Solution**
   João M. L. P. Caldeira, José A. F. Moutinho, Binod Vaidya, Pascal Lorenz, and Joel J. P. C. Rodrigues
   The Second International Conference on eHealth, Telemedicine, and Social Medicine (eTELEMED 2010), St. Maarten, Netherlands Antilles, February 10-15, 2010, pp. 119-124. (**Received the Best Paper Award**)

Resumo

Esta tese centra-se no estudo das redes de sensores sem fios usando nós sensores móveis em cenários para promoção da saúde. A melhoria da qualidade de vida dos pacientes hospitalizados é abordada neste trabalho de investigação através da proposta de uma solução que possa ajudar esses pacientes a manter a sua mobilidade (sempre que possível). A solução proposta, permite o controlo remoto, em tempo real e sem interrupções do estado de saúde dos pacientes. Pequenos nós sensores, capazes de recolher e enviar, através de comunicações sem fios, parâmetros fisiológicos, permitem a monitorização do estado de saúde dos pacientes. Uma infraestrutura de rede, constituída por diversos pontos de acesso, permite a ligação dos nós sensores transportados pelos pacientes, aos prestadores de cuidados de saúde remotos. Para garantir o acesso contínuo e em tempo-real aos nós sensores, dá-se uma atenção especial à gestão da transição desses nós sensores entre as várias áreas de cobertura dos diferentes pontos de acesso. O processo de alteração do ponto de acesso que serve um determinado nó sensor é chamado de transição (*handover*).

Neste contexto, o presente trabalho de investigação propõe um novo mecanismo de transição (*handover*) entre pontos de acesso que possa garantir ligação contínua aos nós sensores móveis numa rede de sensores sem fios aplicada à saúde. Devido aos recursos limitados existentes nos nós sensores, nomeadamente a quantidade de energia disponível (tipicamente estes nós sensores são alimentados por pequenas baterias), o mecanismo proposto tem em atenção a otimização do consumo de energia. Para atingir esta optimização, parte deste trabalho é dedicada à construção de um pequeno nó sensor.

O mecanismo de transição (*handover*) proposto é chamado *Hand4MAC*. Este mecanismo é comparado com outros mecanismos vulgarmente usados na gestão de operações de transição (*handover*) entre pontos de acesso. O mecanismo *Hand4MAC* é construído, demonstrado e validado em dois senários diferentes, por simulação e num protótipo real. Os cenários utilizados replicam a estrutura de uma enfermaria hospitalar. A avaliação do desempenho foca-se essencialmente na percentagem de tempo que os nós sensores estão acessíveis à rede, enquanto se movem através das várias áreas de cobertura de diferentes pontos de acesso e no consumo de energia despendido no processo de transição (*handover*). As experiências realizadas tiveram em conta vários parâmetros, nomeadamente o número de mensagens enviadas, o número de mensagens recebidas, a quantidade de mensagens *multicast* usadas, o consumo de energia, o número de nós sensores presentes no cenário, a velocidade dos nós sensores e o valor do TTL (*time-to-live*) utilizado. Nos testes realizados, em ambos os senários, simulação e real, o mecanismo *Hand4MAC* mostra melhor desempenho do que todos os outros mecanismos de transição (*handover*) considerados. Na avaliação

comparativa foram apenas considerados os mecanismos de transição (*handover*) mais promissores propostos na literatura.

Palavras-chave

Redes de Sensores sem Fios Aplicadas à Saúde, Redes de Sensores sem Fios, Redes de Sensores Corporais, Monitorização em Mobilidade, Saúde Digital, Transição entre Pontos de Acesso, Mobilidade Intra-rede.

Resumo Alargado

Introdução

Este resumo alargado, escrito em Português, descreve o trabalho de investigação apresentado na tese de doutoramento com o título "*Performance Assessment of Mobility Solutions for IPv6-based Healthcare Wireless Sensor Networks*". Na parte inicial, este resumo inclui a identificação do enfoque e enquadramento da tese, a definição do problema, os objetivos, o argumento da tese e as suas principais contribuições. De seguida é descrita a problemática da ligação contínua aos nós sensores móveis em redes de sensores sem fios (RSSFs) aplicadas à saúde (RSSFASs). O texto segue com a descrição de um novo mecanismo de suporte à ligação contínua com nós sensores móveis baseado em características intrínsecas das RSSFASs. Para finalizar, termina com uma breve discussão das principais conclusões e a apresentação de algumas sugestões para investigações futuras.

Enquadramento da Tese

As tecnologias das redes de sensores sem fios (RSSFs) atingiram, nos últimos anos, o topo dos tópicos de investigação [1-3]. Actualmente, estas redes são uma das tecnologias mais promissoras no desenvolvimento do futuro [4-6], onde se inclui a visão adoptda pelo conceito *Internet-of-things* (IoT). Vários sensores pequenos capazes de recolher dados e de os compartilhar, usando ligações sem fios, através da *Internet* são os fundamentos das RSSFs [7]. Estas tecnologias são utilizadas para dar resposta a vários desafios em diferentes áreas, como por exemplo, a vigilância em cenários militares, na monitorização de estruturas de edifícios, o seguimento de animais, a detecção de incêndios florestais, na monitorização de tráfego rodoviário, na monitorização ambiental e em soluções aplicadas à saúde [8-10].

As redes de sensores sem fio aplicadas à saúde (RSSFASs) são um campo específico das RSSFs, quando estas são usadas na criação de soluções para a promoção de saúde [11,12]. Este campo tem-se tornado numa das aplicações mais promissoras das RSSFs [13]. Hoje em dia, nas enfermarias dos hospitais, as equipas médicas realizam a maioria das tarefas de monitorização e acompanhamento junto dos pacientes em intervalos de tempo periódicos [14]. Este comportamento não permite um controlo em tempo-real sobre os parâmetros monitorados. Desta forma, pode tornar-se difícil, em alguns casos, efectuar um acompanhamento mais apertado sobre alguns parâmetros de saúde que precisem de mais atenção. O uso de pequenos sensores ligados aos pacientes podem ser a solução ideal para realizar as tarefas de monitorização em tempo-real [15,16]. Estas soluções podem também potenciar um controlo mais preciso e apertado sobre determinados parâmetros de saúde em pacientes que sofram de doenças que necessitem uma maior atenção nesses mesmos parâmetros [17]. Estes sensores, (conhecidos como nós sensores na terminologia das RSSFs) compatíveis com tecnologias de redes sem fios, podem ser usados numa RSSFAS para recolher e enviar dados para locais remotos [18]. Esta capacidade permite a monitorização e o controlo do estado de saúde dos pacientes à distância, ou seja, em centros de cuidados de saúde [19 ,20]. Desta forma, os dados recolhidos pelos nós sensores podem ser acedidos em qualquer lugar e a qualquer momento, através da *Internet*. Apesar de todo esse potencial, os nós sensores são dispositivos pequenos, com recursos limitados e, como tal, com algumas limitações [21]. Normalmente, esses nós sensores são compostos por quatro partes principais, a saber, módulo sensorial, módulo de processamento, módulo de comunicação e o módulo de alimentação energética [22]. O módulo sensorial fornece a capacidade de recolher determinados parâmetros; o módulo de processamento inclui o microcontrolador que determina a capacidade do nó sensor para executar programas e processar dados; o módulo de comunicação é capaz de enviar dados para uma rede sem fios, tipicamente compatíveis com a norma IEEE 802.15.4 [23,24]; finalmente, o módulo de alimentação inclui a fonte de energia que mantém o nó sensor vivo [25].

A possibilidade de mobilidade dos nós sensores tornou-se recentemente num novo desafio junto da comunidade científica e na investigação em RSSFs [26,27]. A mobilidade dos nós sensores nas RSSFs pode ser classificada em dois grupos, nomeadamente, mobilidade fraca e mobilidade forte [28]. A mobilidade fraca não é caracterizado por um movimento efectivo dos nós sensores. Ela ocorre quando numa rede um nó sensor fica fora de serviço por algum motivo. A mobilidade forte é baseada no movimento efectivo dos nós sensores. Esta característica pode ser atribuída a estes nós sensores pelo fenómeno que eles monitorizam (por exemplo, velocidade do vento ou caudal da água) ou pelas características dos próprios nós sensores.

Quando os pacientes estão hospitalizados devem manter a sua mobilidade, tanto quanto possível, com o objectivo de promover a sua qualidade de vida e melhor recuperação. Isso significa que as RSSFASs usadas para monitorizar pacientes hospitalizados devem oferecer suporte à mobilidade dos sensores transportados por esses pacientes. O suporte à mobilidade em RSSFASs traz novos desafios e problemas à evolução destas redes, desta forma, este tópico de investigação tornou-se um tema com grande importância nas RSSFASs [29].

O tema deste trabalho limita-se ao campo da gestão da mobilidade dos nós sensores numa RSSFAS. Este trabalho de investigação foca-se nos desafios colocados pela capacidade dos nós sensores de uma RSSFAS poderem mover-se livremente numa área coberta por vários pontos de acesso à rede. Assim, este trabalho de investigação é dedicado à busca de soluções que permitam ter ligação contínua aos nós sensores móveis numa RSSFAS com o menor consumo de energia possível. O mecanismo proposto nesta tese dá uma atenção especial à ligação contínua aos nós sensores móveis e ao consumo de energia na gestão da ligação à rede.

Descrição do Problema e Objetivos da Investigação

A mobilidade dos nós sensores nas RSSFASs é hoje a resposta a muitas aplicações desta tecnologia. No entanto, esse recurso traz vários novos problemas para a temática das RSSFASs [26]. Um desses problemas é como manter o acesso à rede dos nós sensores enquanto estes se movem. A natureza deste problema vem da limitação das áreas de cobertura dos pontos de acesso (cerca de 10 metros em cenários interiores e 30 metros em cenários de campo aberto) [30]. Esta limitação implica a utilização de vários pontos de acesso (PAs) para cobrir toda uma área a monitorizar, como por exemplo, o edifício de uma empresa, um armazém, uma casa, um hospital, ou mesmo uma enfermaria de um hospital. Diversas soluções foram propostas na literatura para resolver o problema da transição entre PAs (denominado de *handover*) por parte dos nós sensores quando estes se deslocam entre várias áreas de cobertura [31]. No entanto, estas soluções ainda não se mostram totalmente satisfatórios para assegurar uma ligação contínua entre os nós sensores móveis e a rede. Esta garantia torna-se essencial em aplicações para a saúde. A maioria das soluções existentes usam a metodologia da proposta *Neighbor Discovery* (ND) [32] para gerir as ligações entre os nós sensores e os PAs. A abordagem ND faz uso intensivo de mensagens *multicast*. Este comportamento aumenta o gasto de energia dos nós sensores devido à natureza do processamento deste tipo de mensagens. Sendo assim, deveria ser privilegiada a utilização de mensagens *unicast*, tornado desta forma, as soluções mais eficazes ao nível do consumo energético.

A identificação do momento exato para realizar a transição (*handover*) é um ponto chave para garantir a ligação contínua aos nós sensores. Se esse momento for muito optimista pode causar a existência de muitas transições (*handovers*) indesejáveis, o que provoca muita instabilidade na definição de um acesso válido ao nó sensor. Se, pelo contrário, este momento for muito pessimista, pode levar a períodos de inacessibilidade por parte dos nós sensores [33]. A maioria das soluções de transição (*handover*), propostas na literatura, trocam mensagens em intervalos muito curtos para obter informações sobre a qualidade da ligação entre os nós sensores e os PAs [34-40]. Esta informação é depois utilizada para avaliar a necessidade de realizar, ou não, uma transição (*handover*). Mas, a constante troca de mensagens contribui para uma rápida drenagem das baterias e, portanto, a redução do tempo de vida dos nós sensores. Como tal, se as soluções de transição (*handover*) utilizarem uma abordagem optimista, os gastos energéticos na rede aumentam exponencialmente. Por outro lado, se for utilizada uma abordagem pessimista, os nós sensores podem ficar inacessíveis durante longos períodos. Os nós sensores são pequenos dispositivos alimentados tipicamente por baterias e, portanto, com restrições energéticas bastante elevadas [41]. Uma vez, que os nós sensores dependem da sua energia para se manterem vivos, esta deve ser preservada e assim contribuir para o aumento do tempo de vida desses nós sensores.

O principal objetivo deste trabalho é apresentar e validar um novo mecanismo de transição (*handover*) para nós sensores móveis em RSSASs com suporte a ligação contínua dentro da mesma rede. O mecanismo a propor deve considerar as restrições de energia dos nós sensores. Dessa forma, os custos da sinalização usada devem ser minimizados. Para atingir esta característica, o número de mensagens trocadas entre os PAs e os nós sensores deve ser reduzida ao mínimo. Devido à sua natureza, as mensagens *multicast* têm um forte impacto no consumo de energia da rede. Tendo este facto em conta, uma atenção especial deve ser dedicada à tentativa de redução do uso de mensagens *multicast* no mecanismo transição (*handover*) proposto.

Para alcançar o objetivo principal desta tese, foram identificados e realizados os seguintes objectivos intermédios:

1. Será realizado um estudo abrangente e profundo sobre RSSFs para compreender em detalhe as suas características, limitações e desafios. O estudo deve ser orientado para a aplicação das RSSFs em cenários de saúde. Nesses cenários a ligação contínua aos nós sensores móveis torna-se uma característica fundamental. As soluções propostas na literatura que poderiam ser usadas no suporte à mobilidade de nós sensores em RSSFs serão cuidadosamente estudadas e revistas. Dessa forma, um conhecimento profundo será obtido do estado da arte das redes de sensores móveis. Posteriormente, será dedicada uma atenção especial à compreensão da problemática da ligação contínua aos nós sensores móveis, ou seja, aos mecanismos de transição (*handover*).
2. Para compreender em pormenor as limitações dos recursos existentes nos nós sensores, um dos objetivos intermédios desta tese é a construção de um desses dispositivos. O nó sensor a ser desenvolvido pode ajudar as equipas médicas a recolher a temperatura intra-vaginal das mulheres. A construção deste dispositivo surgiu do facto de não terem sido encontradas na literatura soluções disponíveis para esse efeito. Será dada uma atenção especial à concepção deste dispositivo uma vez que deve ser adequado para colocar dentro da vagina de uma mulher. Além disso, o sensor a criar deve incluir todas as tecnologias sem fios necessárias à sua integração numa RSSFASs. Tendo em conta estas características, este objectivo intermédio constitui um grande desafio no desenho, concepção e construção de um dispositivo de tamanho bastante reduzido.
3. A mobilidade dos nós sensores traz vários problemas novos às RSSFs. Um desses problemas está relacionado com a forma de manter a ligação dos nós sensores à rede quando estes se movem entre várias áreas de cobertura de vários PAs. Desta forma,

um outro objetivo intermédio será definir e propor um novo mecanismo de transição (*handover*) que possa garantir uma ligação confiável e contínua aos nós sensores. Este mecanismo deve também minimizar os gastos de energia dos nós sensores durante o seu funcionamento.

4. Para avaliar as características propostas para o novo mecanismo de transição (*handover*) deve ser realizada a sua validação utilizando ferramentas de simulação. A comparação do desempenho do mecanismo a propor com outras soluções existentes na literatura constitui também parte deste objetivo intermédio.
5. Finalmente, o último objectivo intermédio compreende a construção de uma *testbed* real. Esta *testbed* será usada para validar a aplicação do mecanismo de transição (*handover*) a propor num cenário real. Para garantir a coerência com o objetivo principal desta tese, o mecanismo a propor será avaliado tendo em conta a garantia da ligação contínua aos nós sensores e a optimização dos gatos energéticos.

Argumento da Tese

Esta tese propõe um novo mecanismo de transição (*handover*) para suporte à ligação contínua a nós sensores móveis em RSSFASs otimizando os gastos de energia nessa operação. Em particular, o argumento da tese é o seguinte:

A aplicação dos conceitos de RSSFs em cenários de saúde revelou-se particularmente valiosa na melhoria dos cuidados de saúde prestados aos pacientes. Para que se possa obter informações válidas e atualizadas, do estado de saúde dos pacientes, os nós sensores transportados por esses pacientes devem ter um acompanhamento em tempo-real. Para promover uma melhor qualidade de vida aos pacientes, quando hospitalizados, estes devem manter a sua mobilidade, tanto quanto possível. Vários PAs cobrem os serviços de saúde com acesso sem fios à rede, desta forma, para manter os nós sensores (transportados pelos pacientes) ligados à rede devem ser usados mecanismos de transição (handover) entre PAs. Estas transições devem prevenir a existência de períodos de inacessibilidade. Os nós sensores transportados pelos pacientes devem ser pequenos e confortáveis para que possam ser fixados ao corpo humano sem causar incómodo. Devido a estas características, estes dispositivos têm várias limitações, principalmente, ao nível das suas restrições de energia. Sendo assim, os mecanismos de apoio a mobilidade devem ser extremamente optimizados de forma a reduzir os seus gastos energéticos ao mínimo. Essas características são vitais para a construção de RSSFASs confiáveis.

Para dar suporte a este argumento foi adotada a seguinte abordagem na investigação.

O domínio das RSSFs é cuidadosamente estudado para compreender, em particular, a problemática do uso de nós sensores móveis e o seu impacto no funcionamento dessas redes, quando aplicadas em cenários para a saúde. São estudadas e revistas as principais soluções propostas na literatura que lidam com este problema nas RSSFASs. Após esse estudo, são depois analisados os desafios, limitações e problemas associados às soluções de apoio à mobilidade propostas na literatura.

Os nós sensores são um elemento condicionador nas RSSFASs. Eles são pequenos dispositivos com todos os tipos de limitações, principalmente, baixo poder computacional, comunicações de curto alcance e energia disponível limitada (normalmente usam baterias recarregáveis). Para uma compreensão detalhada destas limitações e a necessidade de as optimizar, é construído de um nó sensor. Esta tarefa ajuda a adquirir conhecimentos essenciais usados depois na concepção de algoritmos e protocolos otimizados para este tipo de dispositivos, com reais benefícios.

Devido às limitações dos nós sensores, os algoritmos de gestão da ligação à rede devem minimizar o número de mensagens trocadas e reduzir ao mínimo os gastos de energia. Os mecanismos de transição (*handover*) gerem a ligação dos nós sensores móveis às RSSFASs. Na promoção de cuidados de saúde é importante fornecer informação atualizada das condições de saúde dos pacientes a qualquer momento e em tempo-real. Para alcançar este propósito, os nós sensores transportados pelos pacientes, devem estar sempre ligados à rede e acessíveis para uma eficaz monitorização remota. A ligação contínua dos nós sensores à rede em cenários cobertos por vários PAs, é suportada por mecanismos de transição (*handover*). Para optimizar as operações destes mecanismos é analisada uma nova abordagem.

Para construir um mecanismo de transmissão mais eficiente que possa ser usado em RSSFASs são considerados os seguintes pressupostos:

1. Os nós sensores percorrem várias áreas de cobertura de vários PAs, mas sempre dentro do mesmo domínio de rede, ou seja, o endereço *Internet Protocol* (IP) dos nós sensores é sempre o mesmo (nunca é alterado).
2. Após um curto período de tempo, os nós sensores passam a ser conhecidos pela RSSAS e esses nós sensores tenderão a permanecer os mesmos durante longos períodos de tempo (ou seja, não será comum os nós sensores serem trocados).

Com base nestes dois pressupostos, o novo mecanismo de transição (*handover*) propõe que sejam os PAs a procurar os nós sensores na sua abrangência, em vez do contrário. Esta opção permite eliminar a necessidade dos nós sensores estarem constantemente a transmitir mensagens para avaliar a sua ligação com o PA ao qual estão registados. Esta ideia considera que devem ser os PAs a procurar por um nó sensor específico, em vez da necessidade de monitorizar continuamente a qualidade da ligação entre os nós sensores e os PAs. Se um PA a determinado momento encontrar esse nó sensor e este escolher fazer a transição (*handover*), esse PA pára de procurar por esse nó sensor. Se um nó sensor se encontrar numa área de cobertura sobreposta à de outro PA, ele começa a receber notificações da sua procura por parte desse novo PA. Nesse momento, o nó sensor pode decidir realizar ou não uma transição (*handover*). Esta decisão pode ser baseada na avaliação do valor da força do sinal recebido. Caso o novo PA tiver um valor da força do sinal recebido superior ao do PA actual, é realizada a transição (*handover*). Caso contrário, o nó sensor permanece com o PA actual.

Para demonstrar as vantagens deste novo mecanismo de transição (*handover*), este é testado usando ferramentas de simulação, e o número de mensagens trocadas é utilizado para a avaliação. A avaliação inclui também diversas variações, no número de nós sensores presentes no cenário, nos valores de *Time-to-Live* (TTL) usados, e na velocidade do movimento dos nós sensores.

De seguida, a utilização deste novo mecanismo é analisada num cenário real. Os resultados obtidos são usados tanto para demonstrar a efectiva ligação contínua e em tempo-real aos nós sensores, como para confirmar o reduzido consumo de energia do mecanismo de transição (*handover*) proposto.

Principais Contribuições

As principais contribuições científicas que resultam do trabalho de investigação apresentado nesta tese são descritas de forma breve nesta secção.

A primeira contribuição desta tese corresponde a um estudo detalhado e abrangente das soluções de suporte à mobilidade em RSSFASs. Os princípios utilizados na construção de RSSFASs são diferentes dos usados em RSSF. Este estudo aponta essas diferenças e destaca as características especiais das RSSFASs. É evidenciada a necessidade de mobilidade nestas redes como uma característica essencial. Tendo por base o contexto desta tese, foi dedicada uma atenção especial ao estudo de mecanismos de transição (*handover*) existentes na literatura que suportem a mobilidade de nós sensores em RSSFASs. Este estudo termina com a identificação de várias questões em aberto relacionadas com a problemática do apoio à mobilidade em RSSFASs. O estudo em causa foi aceite para publicação no IEEE *Sensors Journal* como um artigo de *survey* [31] e está incluído no capítulo 2 desta tese.

A construção de um dispositivo nó sensor era parte dos objectivos intermédios desta tese, desta forma, a segunda contribuição é a proposta de um novo dispositivo nó sensor para recolha de parâmetros de saúde de pacientes. Este dispositivo integra todos os requisitos necessários para a sua integração numa RSSFAS. Ao realizar uma revisão da literatura, foi possível detectar a falta de soluções para recolha e monitorização da temperatura intra-vaginal das mulheres, em tempo-real. Sendo assim, esta proposta inclui a construção de um novo biossensor capaz de monitorizar a temperatura intra-vaginal. Este biossensor integra a capacidade de comunicação sem fio adequada às RSSFASs (ou seja, compatível com o standard IEEE 802.15.4). Os detalhes da construção deste novo nó sensor são apresentados no capítulo 3 desta tese sob a forma de um artigo publicado na revista *Sensores* [42].

A terceira contribuição desta tese destaca os princípios básicos utilizados na concepção e construção do novo mecanismo de transição (*handover*) proposto. Esta contribuição descreve o protocolo de mensagens definido para o novo mecanismo e demonstra as vantagens deste em comparação com as abordagens usadas mais frequentemente. Esta contribuição integra o capítulo 4 desta tese como um artigo publicado na revista *IEEE Communications* [43]. A *ComSoc Technology News* (CTN) (http://www.comsoc.org/ctn) distinguiu esta publicação na edição CTN de julho de 2012 (http://www.comsoc.org/ctn/towards-ubiquitous-mobility-solutions-body-sensor-networks-healthcare).

A seguinte contribuição desta tese corresponde a uma descrição detalhada da construção e operação do mecanismo de transição (*handover*) proposto. Esta contribuição apresenta inicialmente o cenário de uma enfermaria usado no desenvolvimento deste novo mecanismo. De seguida, foi efectuada a avaliação de desempenho do mecanismo proposto, a qual foi comparada com as soluções mais populares utilizadas para transição (*handover*) em RSSFs. Esta avaliação foi realizada através de um cenário simulado usando a ferramenta de simulação OMNeT++ [44] com MiXiM [45] (um simulador de redes sem fios móveis para o OMNeT++). Através desta avaliação, foi possível concluir que a solução de transição (*handover*) proposta (chamada *Hand4MAC*) garante aproximadamente 98% de tempo de ligação aos nós sensores usando 535% menos mensagens recebidas, 735% menos mensagens enviadas e 1840% menos mensagens do tipo *multicast*. Estes resultados foram apresentados num artigo aceite para publicação na revista *Telecommunications Systems* [46]. O artigo em causa compõe o capítulo 5 desta tese.

A próxima contribuição desta tese consiste na análise da aplicação do mecanismo *Hand4MAC* em cenários com diferentes números de nós sensores. Por outro lado, para demonstrar a flexibilidade deste mecanismo, são também usados diferentes valores de velocidade no movimento dos nós sensores. Os resultados obtidos com as experiências realizadas são comparados com as soluções de transição (*handover*) mais comuns relativamente, ao tempo necessário para efectuar uma transição (*handover*), ao número de transições (*handovers*) realizadas, ao número de mensagens trocadas e ao consumo de energia. As experiências são realizadas usando a ferramenta de simulação OMNeT++. O cenário utilizado para a aplicação dos mecanismos de transição (*handover*) simula uma enfermaria de um hospital. Os resultados mostram que usando o mecanismo *Hand4MAC* a conectividade com os nós sensores não se altera significativamente nem com o aumento do número de nós sensores no cenário nem com o aumento da velocidade destes. Usando o mecanismo *Hand4MAC*, os valores de ligação à rede mantiveram-se entre os 92% e os 98% e com valores de consumo de energia bastante reduzidos em todas as situações avaliadas. Esta contribuição é integrada no capítulo 6 como um artigo submetido para publicação numa revista internacional [47].

A sexta e última contribuição desta tese, inclui a construção de uma *testbed* laboratorial de uma RSSFAS para a avaliação do desempenho do mecanismo *Hand4MAC* num cenário real. Usando esta testbed, o desempenho do *Hand4MAC* foi comparado com as soluções mais comuns utilizadas na gestão de transições (*handovers*) em RSSFs. Esta avaliação confirmou os resultados obtidos por simulação. O mecanismo Hand4MAC garante uma ligação quase contínua aos nós sensores com um menor gasto energético. Esta situação foi comprovada com base no menor número de mensagens trocadas entre os elementos da rede quando usado o mecanismo *Hand4MAC*. Um dos principais parâmetros no desenho de mecanismos de transição (*handover*) é o intervalo de tempo (denominado de *Time-to-Live* (TTL)) utilizado na troca de mensagens entre os PAs e os nós sensores para determinar se estes ainda estão acessíveis uns aos outros. Este parâmetro também influencia significativamente o desempenho destes mecanismos, ou seja, dependendo do seu valor, ele aumenta ou diminui o número de mensagens trocadas entre os PAs e os nós sensores. Desta forma, diminuindo o valor do TTL contribui para a redução do número de mensagens utilizadas, mas possivelmente também reduz a conectividade dos nós sensores. Por outro lado, o aumento do valor do TTL aumenta o número de mensagens trocadas e, portanto, os gastos energéticos. Esta contribuição integra também um estudo detalhado sobre a influência dos valores do TTL nos mecanismo de transição (*handover*) estudados, incluindo o *Hand4MAC*. Esta contribuição está incluída no capítulo 7 desta tese na forma de um artigo aceite para publicação no *The International Journal of Ad Hoc and Ubiquitous Computing* [48].

Princípios de Operação de Redes de Sensores sem Fios Aplicadas à Saúde

As redes de sensores sem fios (RSSFs) tradicionais são na sua grande maioria aplicadas para recolha de dados de fenômenos específicos [49-54]. Normalmente, estes fenômenos não necessitam de um controlo apertado (ou seja, em tempo-real) e a recolha dos dados pode ser esparsa. As redes de sensores sem fios aplicadas à saúde (RSSFASs) permitem, como o próprio nome indica, o controlo do estado de saúde de seres humanos. A precisão com que é feito esse controlo pode ser a diferença entre a vida e a morte. Seguindo este princípio, pode ser constatado que existem várias diferenças entre as RSSFs tradicionais e as RSSFASs. Desta forma, são destacados a seguir os princípios fundamentais das RSSFASs:

- Monitorização em tempo-real. Numa RSSFAS é importante ter acesso contínuo aos nós sensores transportados pelos pacientes [12]. Este recurso permite um controlo apertado sobre o estado de saúde dos pacientes. Desta forma, se um comportamento anormal se verificar num dos parâmetros de saúde monitorizados, o sistema pode detectar e alertar imediatamente o pessoal médico para essa situação [55].

- Movimento aleatório e contínuo dos nós sensores. Devido ao facto dos nós sensores serem transportados por pessoas que se movimentam de forma aleatório e constante, as RSSFASs devem suportar mecanismos de suporte à mobilidade rápidos e sem interrupções [35,36]. Estes mecanismos são o ponto-chave para garantir um acesso contínuo e em tempo-real aos nós sensores.
- Áreas de cobertura dos pontos de acesso (PAs) pequenas. Dentro de edifícios as áreas de cobertura dos PAs são drasticamente reduzidas devido à dificuldade de propagação dos sinais [30]. Por exemplo, usando um nó sensor SHIMMER (nó sensor desenvolvido para aplicações na área da saúde), a área de cobertura conseguida dentro de um edifício situa-se em média entre os 5 e os 10 metros [56]. Tipicamente, a construção de uma RSSFAS tem lugar no interior de um edifício, sendo assim, no desenho deste tipo de redes devem ser consideradas áreas de cobertura bastante pequenas, (de apenas alguns metros), entre todos os elementos da rede.
- Uso de vários pontos de acesso para cobrir toda a área a monitorizar. Como visto no ponto anterior, esta necessidade advém do facto de em ambientes interiores termos áreas de cobertura bastante limitadas.
- Tempos curtos para realização de transições (*handovers*). A transição (*handover*) é uma tarefa crítica no suporte da mobilidade em redes sem fios. Para garantir uma ligação contínua e em tempo-real aos nós sensores, o processo de mudança de registo com os PAs, quando um nó sensor transita entre diferentes áreas de cobertura, deve ser curto [37]. Caso contrário, os nós sensores podem ficar inacessível por longos períodos de tempo, evitando desta forma a monitorização contínua.
- Optimização do tempo de vida das baterias dos nós sensores. Os nós sensores dependem das suas baterias para se manterem vivos. A redução do desperdício de energia nas operações realizadas pelos nós sensores é essencial para aumentar os seus tempos de vida [57]. Assim, o desenvolvimento de algoritmos e processos optimizados para estes dispositivos é extremamente importante.

O uso de RSSFASs pode contribuir para melhorar os sistemas de suporte de vida. Como descrito acima, se estas tecnologias poderem assegurar um controlo rigoroso do estado de saúde dos pacientes, podem reduzir o tempo necessário para detectar situações anormais quando comparadas com a utilização dos métodos tradicionais. Portanto, o uso destas tecnologias pode garantir um serviço mais eficiente nos cuidados de saúde prestados e ajudar as equipas médicas a antecipar situações anormais de que os pacientes possam sofrer. O acesso remoto aos dados dos pacientes também pode melhorar o trabalho colaborativo entre médicos.

Necessidade de Mobilidade em Redes de Sensores sem Fios Aplicadas à Saúde

As RSSFASs pretendem fornecer acesso à rede em toda a área de uma enfermaria hospitalar ou até mesmo de um hospital inteiro. O tamanho dessas áreas pode variar desde umas dezenas até centenas de metros. Devido à área de cobertura limitada de cada ponto de acesso (quando usado em cenários interiores) será necessário o uso de vários PAs para que se possa cobrir toda a área onde se pretende ter acesso à rede.

Para melhorar a qualidade de vida dos pacientes, é importante minimizar o seu sofrimento quando se encontram hospitalizados. Oferecer aos paciente a possibilidade destes poderem caminhar livremente pela enfermaria, sabendo que o controlo do seu estado de saúde não é interrompido, é uma melhoria significativa nos cuidados de saúde prestados. O suporte à mobilidade dos nós sensores transportados pelos pacientes é uma característica importante nas RSSFASs. Devido à necessidade de usar vários PAs, as RSSFASs devem dar suporte ao movimento dos nós sensores entre diferentes áreas de cobertura. Lidar com este comportamento não é fácil nas RSSFASs. Caso um nó sensor perca o contacto com um PA e não esteja ainda registado a um novo, isso significa que este nó sensor deixa de ser monitorizado. Esta situação não deve ser permitida em soluções que necessitam de monitorização contínua e em tempo-real, como é o caso das RSSFASs. Para realizar transições ininterruptas dos nós sensores entre as áreas de cobertura de diferentes PAs torna-se extremamente importante o desenvolvimento de mecanismos de transição (*handover*) robustos. O fato dos nós sensores serem alimentados por baterias (com um curto tempo de vida) leva a que o desenvolvimento dos referidos mecanismos de transição (*handover*) tenha em conta a sua optimização ao nível do consumo energético [58].

Mecanismos de Transição (*handover*)

A transição (*handover*) em RSSF é considerada como o processo de mudança do registo de um PA para outro por parte de um nó sensor quando este se desloca de uma área de cobertura para outra. Esse mecanismo garante a mobilidade dos nós sensores nas RSSFs. Este processo apresenta diversas implicações no princípio de funcionamento deste tipo de redes. Por exemplo, se por alguma razão um nó sensor perde o contato com um PA ou leva muito tempo a registar-se num novo, a desejável comunicação contínua deixa de poder ser garantida. Nas RSSFASs, a comunicação contínua com os nós sensores móveis é garantida através dos mecanismos de transição (*handover*). Estes mecanismos devem ser projectados tendo em consideração as seguintes características:

- O processo de transição deve ser rápido e sem interrupções. A ligação ao nó sensor deve ser conservada durante todo o processo;
- Devido à energia gasta no processo de transição (*handover*), estes devem ser minimizados. Só deve ser realizada uma transição (*handover*) se for estritamente necessária;
- Depois de uma transição (*handover*) bem sucedida, as mudanças na rota para esse nó senso devem ser rapidamente propagadas por toda a rede;
- A sinalização usada na decisão de uma transição (*handover*) deve ser mínima. Devem ser usadas poucas trocas de mensagens na gestão da comunicação contínua com os nós sensores.

Todas estas características pressupõem que os nós sensores operam usando uma bateria e, portanto, com bastantes restrições energéticas. Estas características têm em mente a otimização do tempo de vida dos nós sensores e os princípios de funcionamento das RSSFASs.

Proposta de um Novo Mecanismo de *Handover*

Quando um nó sensor se move entre diferentes áreas de cobertura de vários PAs, este deve transitar o seu registo para que permaneça acessível à rede. Determinar o momento exacto em que deve ser realizada a transição do registo de um nó sensor é uma das situações mais difíceis de tratar nos mecanismos de transição (*handover*). Algumas das propostas descritas na literatura usam uma abordagem denominada de registar-após–quebra. Isso significa que essas soluções permitem que existam períodos de inacessibilidade aos nós sensores. Desta forma, o uso destas abordagens não será o mais indicado quando se pretende garantir um acesso contínuo aos nós sensores. Sendo assim, o mecanismo proposto garante um acesso contínuo aos nós sensores usando uma abordagem denominada de ligar-antes-de-quebrar.

O mecanismo proposto, denominado de *Hand4MAC*, considera os seguintes pressupostos:

- Os nós sensores permanecem sempre dentro da mesma rede, ou seja, o seu endereço de IP nunca é alterado;
- Os nós sensores devem permanecer sempre acessíveis em qualquer ponto da enfermaria;
- Depois de um curto período de tempo, todos os nós sensores passam a ser conhecidos pela rede e não será comum serem alterados.

Assumindo que os nós sensores estão sempre dentro do mesmo domínio de rede, não é necessário suporte aos mecanismos de transição (*handover*) na camada 3 do modelo OSI (*Open Systems Interconnection*). Desta forma, o mecanismo de transição (*handover*) proposto opera na camada 2 do modelo OSI.

As figuras 1 e 2 do capítulo 5, apresentam os fluxogramas de operação dos *firmwares* construídos para os nós sensores e para os PAs que suportam o funcionamento do mecanismo *Hand4MAC*. Quando um nó sensor entra pela primeira vez na rede começa por procurar um PA para se registar. Esta tarefa é realizada através do envio periódico (em intervalos definidos pelo valor de TTL) de mensagens *multicast* do tipo *route advertisement* (RA). Caso um PA receba um RA de um nó sensor cria uma nova entrada em sua *cache table* (CT) local onde armazena o endereço do nó sensor. Esta tabela é usada pelos PAs para procurarem, mais tarde, por todos os nós sensores ali presentes. Esta pesquisa é realizada através do envio de mensagens *unicast* do tipo *find* a cada nó sensor na CT, em intervalos muito curtos (aproximadamente 1 segundo). Caso um nó sensor receber uma mensagem *find*, isso significa que está dentro da área de cobertura de um ponto de acesso com o qual não está registado. Neste momento, o nó sensor envia uma mensagem do tipo *lqi-probe* ao seu PA registado e recebe por parte deste uma mensagem do tipo *lqi-probe-acknowledge*. Caso este envio e recepção falharem, o processo suprime a próxima comparação e segue directamente para o registo com o novo PA. O envio e recepção descrito em cima, é usado para atualizar o valor da força de sinal (LQI) recebido relativo ao PA registado. Em seguida, o nó sensor verifica se o LQI do novo PA é superior ao do PA registado. Se assim for, envia uma mensagem *unicast* do tipo *find-acknowledge* ao novo PA para confirmar o novo registo e envia uma mensagem *unicast* do tipo *break* ao anterior PA registado para o notificar da dissociação. Depois de receber uma mensagem do tipo *break* o PA move a entrada do nó sensor da *registered table* (RT) para a CT. A *registered table* (RT) é usada para armazenar a informação dos nós sensores registados. Esta tabela cria uma nova entrada sempre que o PA recebe uma mensagem do tipo *find-acknowledge*. Nesse instante, o nó sensor é removido da CT e inserido na RT. A cada entrada da RT também está associado um *timestamp* relativo à ação de registo de cada nó sensor. O registo de cada nó sensor deve ser renovado a cada intervalo de tempo TTL. Esta renovação é realizada através do envio, por parte dos nós sensores, de uma mensagem *unicast* do tipo *renew-register* aos seus PAs registados. Os respectivos PAs retornam com o envio de uma mensagem do tipo *renew-register-acknowledge*. Se a renovação não for realizada em tempo útil, o PA move o nó sensor da RT para a CT. Quando todos os nós sensores se tornam conhecidos por todos os PAs, o mecanismo de transição (*handover*) é garantido pelas mensagens *unicast* do tipo *find* enviadas pelos PAs aos nós sensores não registados. Este mecanismo evita que os nós sensores e os PAs necessitem uma troca constante de mensagens apenas para verificar se ainda se encontram acessíveis uns aos outros.

Principais Conclusões

A presente tese propõe um novo mecanismo de transição (*handover*) para RSSFASs que suporte acesso contínuo e em tempo-real aos nós sensores móveis com reduzidos gastos energéticos. Para alcançar este objetivo o trabalho de investigação foi dividido em quatro partes principais. Estas partes podem ser resumidas como se segue: a primeira parte foi dedicada ao estudo do tema da tese e à análise do estado da arte para que pudessem ser identificados os principais desafios em aberto; a segunda parte foi dedicada à compreensão em pormenor das limitações associadas aos nós sensores e a necessidade de otimizar as suas operações; a terceira parte descreveu a proposta de um novo mecanismo de transição (*handover*) de suporte à ligação contínua aos nós sensores móveis com gastos energéticos reduzidos; finalmente, a quarta parte foi dedicada à avaliação de desempenho do mecanismo de transição (*handover*) proposto, tanto através simulação com usando uma *testbed* real.

A primeira parte deste trabalho de investigação foi incluído nos capítulos 1 e 2 do presente documento. Nesta fase, foi realizada uma investigação detalhada sobre o tema da tese, com o objectivo de compreender em profundidade o estado da arte. Em seguida, foi definido e delimitado o foco deste trabalho de investigação e foram descritos os principais objetivos a serem alcançados. No capítulo 1 foram apresentadas também as principais contribuições que resultam deste trabalho. O capítulo 2 apresentou um estudo abrangente sobre o tema da tese, analisando as principais soluções existentes na literatura usadas na gestão de transições (*handovers*) em RSSFs, considerando suas aplicações em RSSFASs. Depois de analisar e identificar as principais limitações das soluções existentes, forma identificadas e discutidas algumas questões em aberto.

O principal objetivo deste trabalho foi propor um novo mecanismo de transição (*handover*) que garanta o acesso contínuo aos nós sensores móveis numa RSSFASs com reduzidos gastos de energia. As soluções existentes na literatura não mostram ainda resultados satisfatórios na garantia de ligação contínua aos nós sensores móveis. Estas soluções foram desenhadas para acessos a pedidos esporádicos aos nós sensores, ou seja, sem necessidade de ligações contínuas. Em cenários de saúde o controlo do estado de saúde dos pacientes necessita ser muito apertado, desta forma, o acesso contínuo aos nós sensores é essencial. Devido às limitações das áreas de cobertura dos PAs (cerca de 10 metros dentro de edifícios), devem ser usados vários para cobrir toda a área de uma enfermaria de um hospital. Neste cenário, os nós sensores podem mover-se entre várias áreas de cobertura de diferentes PAs. Sendo assim, o grande problema é como gerir as transições das ligações dos nós sensores aos diferentes PAs, por forma a garantir uma ligação contínua. Nenhuma das soluções existentes é capaz de determinar o momento exacto para realizar uma transição (*handover*), e mais do que isso, determinar se esta transição é benéfico ou não para a trajetória futura do nó sensor. Sendo assim, as decisões para realizar transições (*handovers*) têm de ser determinadas utilizando as informações recolhidos pelos elementos de rede (PAs e nós sensores). A maioria das soluções de transição (*handover*) propostas na literatura, baseiam a sua operação na avaliação de métricas relativas à qualidade da ligação. Até agora, este tipo de métricas provou ser a melhor opção na avaliação da decisão de realizar ou não uma transição (*handover*). Estas métricas representam a força do sinal usado para transmitir uma mensagem do emissor para o receptor. Elas são simples de obter através da operação normal da própria rede, não sendo necessário a utilização de qualquer *hardware* adicional. Algumas soluções para gestão de transições (*handovers*) propostas na literatura, usam *hardware* adicional para recolher outro tipo de informações, (por exemplo, GPS, radiofrequência, infravermelho, etc), no entanto, a utilização desse *hardware* adicional aumenta o consumo de energia dos nós sensores, o que leva à redução dos seus tempos de vida útil. Os nós sensores utilizados em RSSFASs são pequenos dispositivos alimentados por baterias, tipicamente com pouca capacidade. Sendo assim, reduzir os gastos de energia é vital para os manter em funcionamento.

As métricas utilizadas para a avaliação da qualidade da ligação são tipicamente, ou o *received signal strength indicator* (RSSI) ou o *link quality indicator* (LQI). Os valores obtidos por estas métricas são idealmente proporcionais à distância entre o emissor e o receptor. Para obter o valor destas métricas, basta que o emissor e o receptor troquem uma mensagem. A maioria das soluções para gestão de transições (*handovers*), propostas na literatura, trocam periodicamente mensagens entre os nós sensores e os PAs apenas para avaliar a qualidade da ligação. O número de mensagens trocadas na rede influencia significativamente o consumo de energia dos nós sensores. Desta forma, este trabalho de investigação propôs uma nova abordagem ao processo de gestão de transições (*handovers*) que suprime a necessidade de monitorização contínua do valor da qualidade de ligação entre os nós sensores e os PAs.

A segunda parte deste trabalho, apresentada no capítulo 3, foi dedicada ao estudo das limitações de *hardware* existentes num nó sensor. Para atingir este objetivo parcial, foi desenvolvido uma novo biossensor para recolha da temperatura intra-vaginal. A construção deste novo biossensor permitiu obter o conhecimento necessário para entender em profundidade todas as limitações existentes num nó sensor. Este conhecimento foi também fundamental para a proposta de um novo mecanismo de transição (*handover*) energeticamente otimizado.

A terceira parte deste trabalho de investigação foi descrita nos capítulos 4 e 5. Nesta parte do trabalho, foi proposto um novo mecanismo de transição (*handover*) para suporte à ligação contínua com os nós sensores móveis numa RSSFAS. O mecanismo proposto, denominado *Hand4MAC*, usa uma memória *cache* do lado dos PAs para armazenar a informação sobre todos os nós sensores que já estiveram registados com eles. Esta informação é depois usada para que os PAs tentem entrar novamente em contato com esses nós sensores. Quando um nó sensor sai da área de cobertura de um PA e mais tarde retorna, este nó sensor vai, nessa altura, começar a receber mensagens deste PA. As mensagens usadas neste processo são do tipo *unicast* e quando um nó sensor receber uma destas mensagens decide realizar ou não a transição (*handover*). Esta decisão é realizada através da comparação do valor do RSSI do PA actualmente registado com o valor do RSSI da mensagem recebida do novo PA. A decisão final é baseada no valor mais elevado. Ao contrário dos mecanismos de transição (*handover*) mais comuns, usados em redes de sensores (de agora em diante identificados como mecanismos baseado-RSSI), o *Hand4MAC* evita a necessidade de troca contínua de mensagens para avaliar a qualidade da ligação entre os nós sensores e os PAs. O *Hand4MAC* também suprime a utilização intensiva de mensagens do tipo *multicast*, por parte dos PAs, na procura de novos nós sensores na sua área de cobertura. A validação deste mecanismo foi demonstrada através da realização de várias experiências. Estas experiências confirmaram que o mecanismo *Hand4MAC* garante uma ligação quase contínua aos nós sensores com reduzidos gastos energéticos, quando comparado com os mecanismos baseado-RSSI. As experiências realizadas consideraram duas situações diferentes. Na primeira situação, foi usado o mesmo valor de TTL para os dois mecanismos. Os resultados demonstraram que o mecanismo *Hand4MAC* garantiu que os nós sensores permaneceram ligados à rede 98% do tempo. Já o mecanismo baseado-RSSI garantiu apenas 87% desse mesmo tempo. Relativamente às mensagens trocadas verificou-se que o mecanismo *Hand4MAC* usou, aproximadamente o mesmo número de mensagens recebidas, menos 29% de mensagens enviadas e menos 94% de mensagem do tipo *multicast* que o mecanismo basedo-RSSI. Na segunda situação, foi aumentado o valor do TTL usado no mecanismo baseado-RSSI. Esta alteração pretendia melhorar a percentagem de ligação aos nós sensores. Neste caso, usando o mecanismo baseado-RSSI, a percentagem de ligação aos nós sensores aumentou para aproximadamente 98% do intervalo de tempo considerado. Apesar disso, o número de mensagens trocadas aumentou também significativamente. Quando comparando com o mecanismo *Hand4MAC*, o mecanismo baseado-RSSI, recebeu mais 535% de mensagens, enviou mais 735% de mensagens e usou mais 1840% de mensagens do tipo *multicast*. Como facilmente pôde ser concluído, usando o mecanismo baseado-RSSI e reduzindo o valor do TTL, a percentagem de tempo que os nós sensores permaneceram ligados à rede aumentou. No entanto, o número de mensagens trocadas, nessa situação, também aumentou. Como resultado, o tempo de vida das baterias dos nós sensores foi fortemente reduzido.

A quarta parte deste trabalho inclui os capítulos 6 e 7. Esta parte foi dedicada à avaliação de desempenho do mecanismo *Hand4MAC* em comparação com os outros mecanismos de transição (*handover*) apresentados na literatura. A avaliação de desempenho do mecanismo *Hand4MAC* foi realizada em dois cenários diferentes, um usando ferramentas de simulação e outro com recurso a uma *testbed* real. Usando a ferramenta de simulação OMNeT++, foram realizadas várias experiências num cenário que emulava a enfermaria de um hospital. Estas experiências provaram que o mecanismo *Hand4MAC* garantia uma ligação quase contínua aos nós sensores usando um menor consumo de energia quando em comparação com outras soluções. Foi também demonstrado que o mecanismo *Hand4MAC* era suficientemente flexível para ser aplicado, tanto a situações em que foi aumentada a velocidade de movimento dos nós sensores como a situações em que foi aumentada a densidade de nós sensores. Os resultados obtidos demonstraram que, independentemente do número de nós sensores existentes no cenário e a moverem-se a velocidades entre os 2 m/s a os 5 m/s, o mecanismo *Hand4MAC* garantiu que os nós sensores permaneceram ligados à rede acima de 90% do intervalo de tempo considerado. Os resultados também mostraram que o mecanismo *Hand4MAC* atingiu esse grau de ligação com um menor consumo de energia em comparação com as outras soluções testadas.

Em seguida, o mecanismo *Hand4MAC* foi avaliado e validado através da sua utilização numa *testbed* real. Esta *testbed* foi construída usando seis nós sensores comerciais (SHIMMER), dois pontos de acesso e três robôs móveis (Lego NXT) que simularam os pacientes a deslocarem-se. A avaliação de desempenho neste cenário focou-se na percentagem de tempo que cada nó sensor permanecia acessível à rede e no número de mensagens usadas por cada um dos mecanismos de transição (*handover*) testados. Adicionalmente foi também estudada a influência do valor do TTL na ligação dos nós sensores à rede. Os resultados obtidos demonstraram que, com um TTL de 5 segundos, o mecanismo *Hand4MAC* garantiu que os nós sensores permaneceram ligados à rede cerca de 98% do tempo usando menos 38% de mensagens enviadas, menos 1,9% de mensagens recebidas e menos 98,5% de mensagens do tipo *multicast*, quando comparado com as outras soluções de transição (*handover*) testadas. Os outros valores de TTL usados no estudo foram 10 segundos, 30 segundos e 60 segundos. Os resultados provaram que em todos os casos, o mecanismo *Hand4MAC* garantiu que os nós sensores permaneceram ligados à rede aproximadamente mais 10% do tempo que as soluções de transição (*handover*) mais comuns.

O objetivo principal desta tese foi alcançado mediante a apresentação de um novo mecanismo de transição (*Hand4MAC*) para suporte a acesso contínuo e em tempo-real aos nós sensores móveis em RSSFASs com reduzidos gastos energéticos. Este objectivo foi concluído tendo em conta a composição de *hardware* dos nós sensores, a otimização do *software* e o controlo da troca de mensagens. Além disso, como resultado desta investigação foi também possível demonstrar a flexibilidade do mecanismo *Hand4MAC* para aplicação em situações que necessitem de nós sensores mais rápidos. As contribuições deste trabalho de investigação são susceptíveis de ter relevância no campo das redes de sensores sem fios em geral e das redes de sensores sem fios aplicadas à saúde, em particular.

Como observação final, é importante notar que este trabalho de investigação é parte integrante do projeto nacional AAL4ALL (*Ambient Assisted Living for All*), cofinanciado pelo COMPETE sob o FEDER através do programa QREN. O principal objetivo do projeto AAL4ALL é o desenvolvimento de um ecossistema de produtos e serviços para *Ambient Assisted Living* (AAL) associado a um modelo de negócio e validado através de um piloto em larga escala.

Este trabalho de investigação constitui um grande esforço para alcançar o obectivo principal do projeto AAL4ALL .

Direcções Para Trabalho Futuro

Para concluir, os próximos parágrafos apresentam algumas direcções de pesquisa que podem ser seguidas no futuro e que resultam deste trabalho de investigação.

Quando um novo nó sensor, que entra pela primeira vez na rede, se torna conhecido por um dos PA, poderia ser interessante replicar essa informação pelos outros PAs da rede. O desenvolvimento deste recurso pode ser parte de futuros aperfeiçoamentos do mecanismo *Hand4MAC*. A integração desse recurso poderia eliminar a necessidade de usar mensagens do tipo *multicast* quando um nó sensor entra na área de cobertura de um PA que não o conhece. Com este recurso poderia possivelmente ser aumentada ainda mais o tempo de ligação dos nós sensores à rede e reduzir o número de mensagens do tipo *multicast* usadas.

A integração do mecanismo *Hand4MAC* num cenário real, como seja uma verdadeira enfermaria hospitalar, é parte do trabalho futuro desta investigação. Esta tarefa já está em curso através da sua inclusão no projeto AAL4ALL.

A construção de uma interface amigável para visualizar a informação recolhida e a respectiva localização dos nós sensores num cenário real poderá fazer parte de uma tarefa futura. A interface a construir deve permitir o acesso em tempo-real aos dados recolhidos pelos nós sensores e também algumas configurações remotas sobre esses mesmos nós sensores. Além disso, esta interface deve incluir mecanismos autónomos que detectem valores anormais nos parâmetros de saúde dos pacientes e, a partir daí, acionar um sistema de alertas locais (no edifício) ou remotos, se necessário. Este sistema poderia incluir todos os tipos de redes para a difusão dos alertas, como por exemplo Wi-Fi, sistema global para comunicações móveis (GSM), Ethernet, Bluetooth, etc.

Em termos de desenvolvimento de *hardware* a inclusão de técnicas de carregamento das baterias no próprio nó sensor (*power scavenging technics*) poderiam ajudar a aumentar o seu tempo de vida útil. Além disso, a redução do tamanho dos diversos componentes de *hardware* que compõem os nós sensores, poderia contribuir para a construção de nós sensores mais pequeno e, portanto, mais confortáveis e fáceis de transportar pelos pacientes.

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Abstract

This thesis focuses on the study of mobile wireless sensor networks applied to healthcare scenarios. The promotion of better quality-of-life for hospitalized patients is addressed in this research work with a solution that can help these patients to keep their mobility (if possible). The solution proposed allows remote monitoring and control of patients' health in real-time and without interruptions. Small sensor nodes able to collect and send wirelessly the health parameters allow for the control of the patients' health condition. A network infrastructure, composed by several access points, allows the connection of the sensor nodes (carried by the patients) to remote healthcare providers. To ensure continuous access to sensor nodes special attention should be dedicated to manage the transition of these sensor nodes between different access points' coverage areas. The process of changing an access point attachment of a sensor node is called handover. In that context, this thesis proposes a new handover mechanism that can ensure continuous connection to mobile sensor nodes in a healthcare wireless sensor network. Due to the limitations of sensor nodes' resources, namely available energy (these sensor nodes are typically powered by small batteries), the proposed mechanism pays a special attention in the optimization of energy consumption. To achieve this optimization, part of this work is dedicated to the construction of a small sensor node.

The handover mechanism proposed in this work is called Hand4MAC (handover mechanism for MAC layer). This mechanism is compared with other mechanisms commonly used in handover management. The Hand4MAC mechanism is deployed and validated through by simulation and in a real testbed. The scenarios used for the validation reproduces a hospital ward. The performance evaluation is focused in the percentage of time that senor nodes are accessible to the network while traveling across several access points' coverage areas and the energy expenditures in handover processes. The experiments performed take into account various parameters that are the following: number of sent messages, number of received messages, multicast message usage, energy consumption, number of sensor nodes present in the scenario, velocity of sensor nodes, and time-to-live value. In both simulation and real testbed, the Hand4MAC mechanism is shown to perform better than all the other handover mechanisms tested. In this comparison it was only considered the most promising handover mechanisms proposed in the literature.

Keywords

Healthcare Wireless Sensor Network (HWSN), Wireless Sensor Network (WSN), Body Sensor Network (BSN), Mobile Monitoring, e-Health, Handover, Handoff, Intra-mobility.

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Acronyms

6LoWPAN	Internet Protocol version 6 over Low-power Personal Area Network
AoA	Angle of Arrival
AP	Access Point
BS	Border Sensor
BSN	Body Sensor Network
CAP	Contention Access Period
CCA	Clear Channel Assessment
CFP	Contention Free Period
CPU	Central Processing Unit
CSMA-CA	Carrier Sense Multiple Access with Collision Avoidance
dB	Decibels
ECG	Electrocardiogram
EEG	Electroencephalogram
F-LQE	Fuzzy Link Quality Estimator
GHz	Giga Hertz
GPS	Global Positioning System
GTS	Guaranteed Time Slots
GW	Gateway
HWSN	Healthcare Wireless Sensor Network
IoT	Internet of Things
IP	Internet Protocol
IPv6	Internet Protocol version 6
L2	Open System Interconnection model Layer 2
L3	Open System Interconnection model Layer 3
LQI	Link Quality Indicator
m/s	Meters per Second
mA	Miliamperes
mAh	Miliamperes Hour
MAC	Medium Access Control
microSD	Micro Secure Digital
MN	Mobile Node
ND	Neighbour Discovery
NoP	Network of Proxies
NTC	Negative Temperature Coefficient
OSI	Open System Interconnection
PA	Proxy Agent

PAN	Personal Area Network
PCB	Printed Circuit Board
RA	Router Advertisement
RFID	Radio-frequency Identification
RSSI	Received Signal Strength Indicator
SHIMMER	Sensing Health with Intelligence Modularity, Mobility and Experimental Reusability
SMD	Surface-mount Device
SPo2	Pulse Oximeter Oxygen Saturation
ToA	Time of Arrival
TTL	Time-to-Live
USB	Universal Serial Bus
V	Voltage
W	Watts
WSN	Wireless Sensor Network

Chapter 1

Introduction

This thesis addresses the problematic of continuous communication with mobile sensor nodes in wireless sensor networks (WSNs) applied to healthcare (HWSNs). It proposes a new approach based on intrinsic characteristics of these scenarios. This introductory chapter includes the thesis focus and scope description, the problem definition, the research objectives, the thesis statement, the main contributions for the state of the art, and the thesis organisation.

1 Thesis Focus and Scope

Over the past few years wireless sensor network (WSN) technologies have reached the top of research topics [1-3]. Considering the Internet of Things (IoT) vision, these networks have proven to be one of the most promising technologies for the future [4-6]. Several small sensor nodes able to collect and share data wirelessly over the Internet constitute the basis of the WSNs [7]. Today different research areas use these technologies to solve several challenges in military surveillance, building structure monitoring, tracking animals, fire detection, traffic monitoring, environmental monitoring, and healthcare solutions [8-10].

The application of wireless sensor networks for healthcare solutions is considered a special topic of the WSNs that are identified as healthcare wireless sensor networks (HWSNs) [11, 12]. This field is one of the most promising WSNs applications [13]. Nowadays, most of the monitoring tasks, in hospital wards, are performed by medical staff on patients at periodic time intervals [14]. This behaviour is unsuitable for real-time monitoring of patients' health parameters and in some cases a tight control may fail over parameters that need more attention. To perform health monitoring tasks in real-time small sensor nodes can be used, with biofeedback capabilities, attached to hospitalized patients [15, 16]. By using these sensor nodes, it is also possible to perform more accurate control of bio-parameters on patients suffering from diseases that need close attention [17]. These sensor nodes (with wireless technologies capabilities) can be part of a HWSN and use it to send the collected data to remote locations [18]. This feature allows remote monitoring and control of patients' health in healthcare facilities [19, 20]. Therefore, the data collected by the sensor nodes can be accessed at any time, anywhere over the Internet. However, sensor nodes are tiny devices with limited resources and as such have some drawbacks [21]. Typically, these sensors nodes are comprised of four main modules [22], briefly described as following: the sensing module provides the ability to collect certain parameters; the processing module includes the microcontroller, which determines the capacity of the sensor node to run programs and process data; the communication module which is able to send data wirelessly to a network typically compliant with the IEEE 802.15.4 standard [23, 24]; the power supply module which includes the energy source to keep the node alive [25].

Considering that sensor nodes are able to move, became a new challenge for the WSNs research [26, 27]. The sensor nodes' mobility can be classified into two groups considering either weak or strong mobility [28]. Weak mobility does not represent an effective movement of sensor nodes. It is related to the network reorganization when a node goes out of service for some reason. Strong mobility is used when sensor nodes are able to move. This ability can be assigned to the sensor nodes by the phenomenon being monitored or by the sensor nodes' characteristics themselves.

In order to promote the hospitalized patients' quality-of-life it is important to let them keep their mobility as much as possible. Considering this ability means that HWSNs used to monitor the patients should support and manage the mobility of sensor nodes carried by them. Mobility support in HWSNs brings lots of new challenges and issues to the evolution of these networks and, thereby, it is now a hot research topic in HWSNs [29].

The scope of this thesis is limited to the field of mobility management of sensor nodes in a HWSN. This research work is focused in the challenges raised from the sensor nodes' ability to move freely in an area covered by several access points. Thus, this research work is dedicated to searching for solutions that can have continuous connection of mobile sensor nodes in HWSNs with the lowest energy consumption possible. The mechanism proposed in this thesis plays special attention to continuous connection with the mobile sensor nodes and the energy consumption in the connection management.

2 Problem Definition and Research Objectives

Mobility of sensor nodes in HWSNs is currently the response to many applications of this technology. However, this feature brings several new problems into the HWSNs world [26]. One of these problems is to keep sensor nodes accessible to the network while moving. The nature of this problem comes from the limitation (about 10 meters for indoor and 30 meters for outdoor applications) of access points' (APs) coverage areas [30]. This limitation implies the use of several APs to cover an entire area of, for example, an enterprise building, a store building, a house, a hospital, or even a hospital ward. Several solutions were proposed in the literature to solve the link transition (called handover) between APs and sensor nodes when travelling among different coverage areas [31]. However, these solutions are not satisfactory yet to ensure continuous communication to mobile sensor nodes, as is required in healthcare applications. Most of the existing solutions use neighbour discovery (ND) [32] approach to manage the connection between sensor nodes and APs. The ND approach uses intensive multicast messages. This behaviour increases the sensor nodes' energy expenditures. Therefore, the use of unicast messages should be more effective.

The definition of the exact moment to perform a handover is the key issue to ensure continuous communication to the sensor nodes. If this moment is optimistic it could introduce the existence of several undesirable handovers that causes much instability in the definition of a valid access to the sensor node. If this moment is too pessimistic, it could lead to periods of disconnection by the sensor nodes [33]. Most of the handover solutions, proposed in the literature, exchange messages at very short intervals to get information about the link quality between sensor nodes and APs [34-40]. This information is then used to evaluate the need to perform a handover or not. But the constant exchange of messages contributes to the rapid drain of the batteries and therefore, reducing the lifetime of sensor nodes. As such, if these solutions use an optimist approach, the energy costs in the network increases exponentially. On the other hand, if these solutions choose to use the pessimist approach the sensor nodes could be inaccessible for long periods of time. Sensor nodes are tiny devices powered by batteries and therefore have severe energy constraints [41]. This energy should be preserved in order to increase the lifetime of the sensor nodes.

The main objective of this thesis is to present and validate a new handover mechanism for mobile sensor nodes in HWSNs with continuous communication support within the same network. The proposed mechanism should consider the energy constraints of sensor nodes. Then, the signalling costs should be minimized. To accomplish this feature the number of messages exchanged between APs and sensor nodes should be reduced to minimal. Due to their nature, multicast messages have a strong impact in the network energy consumption. Therefore, special attention should be dedicated to reduce the multicast messages usage in the proposed handover mechanism.

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

1. A comprehensive and meaningful study of WSNs should be performed to understand in detail their characteristics, limitations, and challenges. The study should be oriented to the application of WSNs in healthcare scenarios. In these scenarios continuous communication with mobile sensor nodes is a key feature. The solutions proposed in the literature and related works that could support mobility of sensor nodes in WSNs should be carefully reviewed. That way, a meaningful background is obtained of the

state of the art of mobile WSNs. Thereafter special attention should be dedicated to understanding the problematic of continuous communication with mobile sensor nodes, namely, handover mechanisms.

2. To understand the limitations of sensor nodes' capabilities, the construction of one of these devices forms part of this thesis's intermediate objective. The sensor node to be developed can help physicians to collect the intra-vaginal temperature of women. The construction of this device arose from the fact that available solutions for that purpose are not found in the literature. This device should be suitable to be placed inside a woman's vagina. Also, it should include all the wireless technologies needed to be integrated into a real HWSNs. Taking into account these features, this intermediate objective constitutes a big challenge for the design and construct of a very tiny device.
3. Sensor nodes mobility brings several new issues to WSNs. One of these issues is how to maintain a connection with sensor nodes when they move across several APs coverage areas. Another intermediate objective is to define and propose a new handover mechanism that can ensure a reliable and continuous communication with sensor nodes. This mechanism should also minimize the energy expenditures of sensor nodes in its operation.
4. In order to evaluate the purposes of the proposed handover mechanism its validation using simulation tools should be performed. The comparison of the proposed solution performance with other available solutions is also part of this intermediate objective.
5. The construction of a real testbed is the final intermediate objective to be accomplished. This testbed should validate the application of the proposed handover mechanism in real world. In order to be suitable with the main objective of this thesis the proposed solution should be evaluated for continuous communication with sensor nodes and for energy expenditure optimization.

3 Thesis Statement

This thesis proposes a new handover mechanism to support continuous communication with mobile sensor nodes in HWSNs considering small energy expenditures in this operation. In particular, the thesis statement is the following:

The application of WSNs concepts to healthcare scenarios proved to be particularly valuable in improving health care provided to patients. To provide valuable and updated information (of patients' health state) sensor nodes carried by patients should have real-time monitoring. To promote better quality-of-life to patients they should keep their mobility, as *much as possible. Several APs cover healthcare facilities with network access and therefore to maintain the sensor nodes (carried by patients) connected to the network, handover mechanisms should handle the transitions between APs. These transitions should be seamless and preventing disconnection periods. Sensor nodes carried by the patients should be tiny and confortable to be attached to the human body without any perturbation. Due to these characteristics, these devices have several constraints, mainly, energy constraints. Therefore, the mobility support mechanisms should be tremendously optimized in order to reduce their energy expenditures to the minimum. These achievements are vital to construct reliable HWSNs.*

To support this thesis statement the following research approach was adopted.

The WSNs domain is carefully studied to understand in particular the problematic of using mobile sensor nodes and their impact on the operation of these networks when used for healthcare promotion (called healthcare wireless sensor networks (HWSNs)). The proposed solutions that deal with this problem in HWSNs are reviewed. The challenges, limitations, and issues associated with the proposed mobility support solutions are then analysed.

Sensor nodes are a drawback element in HWSNs. They are tiny devices with all kinds of limitations, mainly, low computational power, short-range communication, and limited available energy (typically rechargeable batteries). For an in-depth understanding of these limitations and the need to optimize them, the construction of one sensor node is done. This construction helps to acquire knowledge essential in designing optimized algorithms and protocols that can be deployed in this type of devices with better benefits.

Due to the sensor nodes' limitations the connection algorithms should both, minimize the number of messages exchanged and the energy expenditures. Handover mechanisms manage the connection of mobile sensor nodes with HWSNs. In healthcare promotion it is important to provide updated information of patients' health conditions in real-time and at any time. To accomplish this purpose the sensor nodes should always be connected to the network and accessible to remote monitoring providers. Continuous connection to the sensor nodes, in scenarios covered by several APs, is supported by handover mechanisms. To optimize the operations of these mechanisms a new approach is analysed.

To construct a more efficient handover mechanism to be used in HWSNs the following assumptions are considered:

1. The sensor nodes moves across several APs' coverage areas always within the same network domain, i.e., the IP address of the sensor nodes is always the same (never changes).

2. After a short period of time, the sensor nodes are well known by the infrastructure and it is uncommon to change these sensor nodes (the sensor nodes remain the same for long periods of time).

Based on these two assumptions the new handover mechanism proposes that APs should search for the surrounding sensor nodes instead the contrary. This option prevents the sensor nodes to be always transmitting messages to evaluate their connection with the current AP. The idea considers that APs should be searching for a specific sensor instead of continuously monitoring the link quality or the RSSI between the sensor and the corresponding AP. If the AP finds this specific node and the node chooses to handover, then the AP stops looking for it. If the sensor node moves into an overlapped coverage area of another AP, it starts to receive finding notifications from this new AP. At this time, the sensor node can decide to perform a handover or not. The decision can be based on the evaluation of the received signal strength value. If the new AP has a better value of received signal strength than the current one, then the handover is performed. If not, the sensor node stays with the current AP.

To demonstrate the advantages of this handover approach it is tested using simulation tools and the number of messages exchanged is used for the evaluation. The evaluation also includes several variations of the number of sensor nodes in the scenario, different TTL values, and the travel velocity of sensor nodes.

The deployment of this approach in a real scenario is then analyzed. The results obtained are used to demonstrate the real-time connection to the sensor nodes and to confirm the reduced energy consumption of the proposed handover mechanism.

4 Main Contributions

The main scientific contributions that emerge from the research work presented in this thesis are briefly described as follows.

The first contribution of this thesis is a detailed and comprehensive study of intra-mobility solutions for HWSNs. The principles used in HWSNs construction are different from WSNs. This study points out these differences and highlights the special characteristics of HWSNs. Also, the mobility demand in these networks is evidenced as an essential feature. Following the scope of this thesis, special attention was devoted to the study of available handover mechanisms, which support the mobility of sensor nodes in HWSNs. This study ends with the identification of several open issues related to the problematic of mobility support in HWSNs. This study was accepted for publication as a survey article in IEEE Sensors Journal [31] and it is included in chapter 2.

As the construction of a sensor node device was part of the intermediate objectives, the second contribution of this thesis is a proposal of a new sensor node device to collect patients' health parameters. This device integrates all the requirements need to be integrated in a HWSN. By performing a literature review it was possible to detect that there was no available solutions for collecting and monitoring the women's intra-vaginal temperature in real-time. Therefore, this proposal includes the construction of a new biosensor for intra-vaginal temperature monitoring. This biosensor integrates wireless communication suitable with HWSNs (compliant with IEEE 802.15.4). The construction details of this new sensor node are presented in chapter 3 as an article published in Sensors [42].

The third contribution of this thesis highlights the base principles used in the design and construction of the new proposed handover mechanism. This contribution describes the message protocol defined for the new handover mechanism and demonstrates the advantages of this new approach compared to other approaches often used. This contribution is integrated in chapter 4 as an article published in IEEE Communications Magazine [43]. ComSoc Technology News (CTN) (http://www.comsoc.org/ctn) distinguished this publication in CTN Issue of July 2012 (http://www.comsoc.org/ctn/towards-ubiquitous-mobility-solutions-body-sensor-networks-healthcare).

The following contribution of this thesis is a detailed description of the handover proposal construction and operation. This contribution presents the ward scenario used for the implementation of this new handover mechanism. After the performance evaluation of the proposed solution was performed, it was compared to the most popular solution used for handover in WSNs. This evaluation was performed through a simulation scenario using the OMNeT++ [44] simulation tool with MiXiM [45] (a wireless and mobile networks simulator for OMNeT++). It was possible to conclude that the proposed handover solution (called Hand4MAC) can ensure 98% connection time to the sensor nodes with 535% less received messages, 735% less sent messages, and 1840% less multicast messages. These results were presented in an article accepted for publication in Telecommunications Systems [46]. This article composes the chapter 5 of this thesis.

The next contribution of this thesis consists of the analyses of the application of Hand4MAC mechanism in scenarios with a higher number of sensor nodes. Also, to prove the flexibility of this mechanism, different velocities for the sensor nodes are used. The results obtained by the performed experiments are compared with other common handover solutions in terms of the time needed to perform a handover, number of performed handovers, number of messages exchanged by the sensor nodes, and energy consumption. The experiments are performed by simulation using the OMNeT++ tool. The scenario used for the application of the handover mechanisms represents a hospital ward. The results show that the connectivity with sensor nodes does not change significantly when increasing their number and their velocity using the Hand4MAC mechanism. The connectivity values of Hand4MAC mechanism remained between 92% and 98% with reduced values of energy consumption in all the situations evaluated. This contribution is presented in chapter 6 as an article submitted for publication in an international journal [47].

The sixth and last contribution of this thesis is the deployment of a HWSN laboratory testbed for the performance evaluation of the Hand4MAC mechanism in a real scenario. Hand4MAC performance was compared to the most used solution for handover in WSNs in a real scenario. This evaluation confirms the results obtained by simulation. The Hand4MAC mechanism can ensure almost continuous connection to the sensor nodes with less energy expenditure. This point was proven due to the reduced number of messages exchanged between network elements using Hand4MAC mechanism. In handover mechanisms one of the main design parameters is the time interval (denoted as time-to-life (TTL) interval) used to exchange messages between APs and sensor nodes in order to determine if they are still accessible to one another. This parameter also significantly influences the performance of these mechanisms, namely, increasing or decreasing the number of messages exchanged by APs and sensor nodes. Decreasing the TTL value contributes to the reduction in the number of messages used but it also reduces the accessibility to the sensor nodes. On the other hand increasing the TTL value increases the number of exchanged messages and therefore the energy expenditures. A detailed study about the influence of TTL values and its variations in Hand4MAC and other handover solution is also part of this contribution. This contribution is included in chapter 7 as an article accepted for publication in The International Journal of Ad Hoc and Ubiquitous Computing [48].

5 Thesis Organization

This thesis is organized into eight chapters. Apart from these first and eighth chapters, which are dedicated, respectively, to the introduction and conclusions and future work, all the other chapters of this thesis are composed of an article published in or submitted to an international journal. The articles that compose this thesis are presented in their original (published) format respecting the journals templates, that way, all the numberings and indexes are in accordance with the articles' templates. Following the structure of the other chapters, the *Introduction* chapter includes, at the end, its own reference list. The next paragraphs summarize the content and organization of the chapters included in this thesis.

Chapter 1 describes the focus and the scope of this thesis as well as the problem definition and identification of the objectives to be accomplished. This chapter also includes the statement of this thesis and summarizes its main contributions. Finally the organization and structure of the thesis is presented.

Chapter 2 introduces the intra-mobility support problematic in HWSNs with special focus on handover mechanisms. After characterising the HWSNs' principles, this chapter presents the handover concept and its importance in supporting continuous connection to mobile sensor nodes. Special attention is devoted to the literature review of existing solutions for intra-mobility support in WSNs and their faults and virtues for use in HWSNs. Then, the characteristics of each of the existing solutions are analysed while keeping in mind their possible application in HWSNs. At the end several open issues are identified for further research.

Chapter 3 presents a new biosensor for registering intra-vaginal temperature. After demonstrating that there are no available solutions in the literature for that purpose, the construction methodologies used in the conception of the biosensor are explained. The proposed biosensor is then evaluated and validated by practical experiments and the results obtained are presented.

Chapter 4 describes the operating principles used to support the mobility of sensor nodes in HWSNs. Based on a ubiquitous concept, how this vision could be embedded in HWSNs is demonstrated. To support the ubiquity in HWSNs a new handover messages protocol is proposed. This new protocol is then evaluated and the results are presented.

In chapter 5, after presenting a brief introduction to mobility support in HWSNs, introduces a new handover approach to support continuous connection with mobile sensor nodes. A detailed description of the construction of this new handover approach (called Hand4MAC) is then provided. After that, the network scenario used to evaluate the Hand4MAC proposal is presented. The second part of the chapter is dedicated to the performance evaluation of the Hand4MAC proposal. This evaluation was performed through simulation tools and the results obtained are then analysed.

Chapter 6 presents the performance assessment of the Hand4MAC mechanism. After a brief introduction to the topic under evaluation and the presentation of the background, this chapter describes the network model used for the performance evaluation including the network setting. Then, the performances assessment takes place and the results obtained are presented. The study of the performance of the Hand4MAC mechanism presented in this chapter includes variations in the number of sensor nodes in the scenario and variations in their velocities. The results analysis involved in this chapter focuses on connection time percentage with sensor nodes, time needed to perform a handover, number of performed handovers, number of messages exchanged, and energy consumption.

Chapter 7 describes the construction of a laboratory testbed to evaluate the performance of Hand4MAC mechanism in a real scenario. This chapter, after a brief introduction and background to mobility support in HWSNs, starts by reviewing the main principles of

Hand4MAC construction. The chapter goes on to describe the testbed deployment and the developed tools to evaluate the implementation and the performance of Hand4MAC approach in real scenarios. In order to demonstrate the advantages of Hand4MAC mechanism several experiments were performed with different TTL values. The results obtained by the performed experiments are analysed and discussed at the end of this chapter.

Finally, chapter 8 summarises the main conclusions and contributions of this thesis and points out further research directions.

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Chapter 2

Intra-Mobility Support Solutions over Healthcare Wireless Sensor Networks – Handover Issues

This chapter consists of the following article:

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Intra-Mobility Support Solutions for Healthcare Wireless Sensor Networks – Handover Issues

João M. L. P. Caldeira, Joel J. P. C. Rodrigues, *Senior Member*, *IEEE*,
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***Abstract*— Currently, several solutions are available for monitoring patient health using body sensors. In hospitals, healthcare wireless sensor networks (HWSNs) offer support to access these sensors to allow for continuous patient monitoring. In order to improve the quality-of-life of hospitalized patients, it is important to let them walk around the monitored area. This ability brings several challenges to HWSNs with mobility support. Due to the crucial importance of the sensed parameters the HWSNs must be in continuous communication with the body sensors. The connection between body sensors and a healthcare wireless sensor network is performed through an access point. Indoor communications are limited in terms of signal propagation and, therefore, several access points to cover large areas are deployed. In order to maintain the sensors' accessibility these should frequently change their point of attachment by performing a mechanism known as a handover. Handover mechanisms are able to support the intra-mobility of sensors in networks within the same domain. This paper surveys the most recent intra-mobility solutions with special focus on handover approaches that can be used in healthcare wireless sensor networks. An in depth review of the related literature is performed in order to present the state of the art on this topic, to discuss the available solutions, and to point out open issues for further research work.**

***Index Terms*— Intra-mobility, handover, healthcare wireless sensor networks, survey**

I. INTRODUCTION

WIRELESS sensor networks (WSNs) technologies have risen to the top of research topics over the past few years [1-3]. Currently, these networks are one of the most promising technologies for the future [4-6], including the Internet of Things (IoT) vision. Several small sensors collecting data and sharing it wirelessly over the Internet are the fundamentals of the WSNs [7]. These technologies are applied to solve several challenges in different areas like military surveillance, building structure monitoring, tracking animals, fire detection in forests, traffic monitoring, environmental monitoring, and healthcare solutions [8-10].

Healthcare wireless sensor networks (HWSNs) are a specific field of wireless sensor networks when applied to healthcare solutions [11]. This field is one of the most promising WSN applications [12]. Nowadays, in hospital wards, the medical staff perform most of the monitoring tasks near the patients at periodic intervals [13]. This behavior does not allow for real-time control over the monitored parameters and in some cases a tight control may fail in some parameters that need more attention. The use of small sensors (with biofeedback capabilities) attached to hospitalized patients could be the ideal solution to perform the regular daily monitoring tasks in real-time [14]. This could also potentiate a more accurate control of bio-parameters of patients suffering from diseases that need close attention [15]. These sensors, (known as sensor nodes in WSNs terminology) compliant with wireless technologies, could be part of a HWSN to send the collected data to remote locations [16]. This ability allows remote monitoring and control of patients' health in healthcare facilities [17, 18]. This way the sensors' data can the accessed anywhere, at any time over the Internet. Despite all this potential, the sensor nodes are tiny devices with limited resources and as such have some drawbacks [19]. Typically, these sensors are comprised of four main parts, namely, sensing module, processing module, communication module, and power supply module [20]. The sensing module provides the ability to collect certain parameters; the processing module includes the microcontroller, which determines the capacity of the sensor node to run programs and process data; the communication module is able to send data wirelessly to a network typically compliant with IEEE 802.15.4 standard [21]; the power supply module includes the energy source to keep the node alive [22].

The enabling mobility of sensor nodes became a new challenge in WSN research [23, 24]. The mobility of sensor nodes can be classified into two groups weak mobility and strong mobility [25]. Weak mobility is not characterized by an effective movement of sensor nodes. It occurs when a node

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goes out of service for some reason. Strong mobility is based on the effective movement of sensor nodes. This feature can be assigned to these sensor nodes by the phenomenon (e.g. wind or water) being monitoring or by the characteristics of the sensor nodes themselves.

When patients are hospitalized they should keep their mobility as much as possible in order to promote their quality-of-life. This means that HWSNs used to monitor hospitalized patients should offer mobility support of the sensor nodes carried by the patients. Supporting mobility in HWSNs brings lots of new challenges and issues to the evolution of these networks and, thereby, it is now a hot topic in HWSNs research [26].

One of the emerging challenges caused by the mobility of the sensor nodes is their network coverage [27]. To deal with this issue HWSNs should enclose multiple access points and support route variations in order to reach each sensor node. Moreover, to get continuous access to the sensor nodes, a valid route to each one at all times must be available [28, 29]. The mechanism to support the point of attachment change to the network is known as handover. One of the most difficult challenges in handover mechanisms is determining the exact moment at which to perform the attachment point change. Several metrics are used to estimate the best moment to perform a handover. The accuracy of handover mechanisms can allow for continuous connection to the sensor nodes in HWSNs. Handover mechanisms support intra-mobility in HWSNs. Intra-mobility is characterized by the mobility of sensor nodes between different access points, but always within the same network domain, i.e., the nodes addresses always remain the same.

This paper surveys the state-of-the art on solutions for intra-mobile support of sensor nodes that can be used in healthcare wireless sensor networks. Special focus is dedicated to the most recent handover mechanisms that support sensor nodes' intra-mobility in these types of networks.

This document is organized as followed: Section II addresses the main principles of healthcare wireless sensor networks while Section III studies the importance of mobility in HWSNs focusing on intra-mobility and handover issues. This section also presents a description of the metrics used for handover decisions. The most recent handover approaches to support intra-mobility are presented in Section IV, and Section V discuses the main features of the handover proposals regarding their application in HWSNs. Some open issues and future research directions are presented in section VI. Finally, Section VII concludes the paper.

II. Healthcare Wireless Sensor Networks Principles

Traditional WSNs are applied mostly to data collection from a specific monitored phenomenon [30-35]. Typically, this phenomenon does not need close control (in real-time) and the data acquisition is sparse on time. HWSNs promote health control of human beings. The accuracy of this control may be the difference between life and death. Starting with this principle there are several variations between traditional and healthcare WSNs. The main principles of HWSNs are the following:

- Real-time monitoring. In HWSNs it is important to have continuous access to the patients' sensors [36]. This feature allows for close control over the patients' health. Then, if an abnormal behavior occurs in the monitored human parameters, the system can detect it and alert the medical staff immediately [37].
- Random and continuous motion of sensor nodes. Due to the fact that sensor nodes are attached to people with random and constant motion, the HWSNs should support fast and seamless mobility mechanisms [38, 39]. These mechanisms are the key point for real-time and continuous access to sensor nodes.
- Short AP's coverage area. Indoor communications are drastically reduced in terms of signal coverage area [40]. For example, with the SHIMMER platform (a sensor node platform developed for healthcare applications) this area averages from 5 to 10 meters [41]. Typically, the construction of a HWSN takes place inside buildings, so the design of these networks must consider only a few meters of signal coverage area between all the elements.
- Use of several APs to cover the whole monitored region due to the limited coverage area of the APs.
- Short times for handover. Handover is a critical task in supporting mobility over wireless networks. To ensure real-time and continuous access to the sensor nodes the process of changing registration between APs must be short [42]. Otherwise, the sensor nodes could be inaccessible for long periods of time avoiding continuous monitoring.
- Desirable long life of nodes' batteries. The sensor nodes depend on their batteries to stay alive. Reducing the waste of energy in sensor nodes' operations is crucial to increase their lifetime [43]. So, the design of optimized algorithms and procedures to operate these devices is extremely important.

The use of HWSNs can contribute to better life support system. As described above if these technologies can ensure a close monitoring of the patients' general health, they can reduce the time required to detect an abnormal situation when compared with traditional methods. Therefore, it can guarantee a more efficient service at healthcare facilities and help medical staff to anticipate timely abnormal health conditions that patients might suffer. The remote access to patients' data can also improve the collaborative work between physicians.

A. The Creation of Healthcare Wireless Sensor Networks

Due to the limited coverage area of APs for indoor applications, it becomes imperative to use multiple APs to cover the entire area of an infirmary, a patient's home or even a hospital [44, 45]. The construction of a HWSN comprises three main elements, namely, *i*) a gateway that acts as a bridge between the HWSN and the outside world (Internet), *ii*) APs that support communication to/from the sensor nodes, and *iii*) the sensor nodes themselves that collect body parameters and send them wirelessly over the network. Fig. 1 illustrates a HWSN architecture.

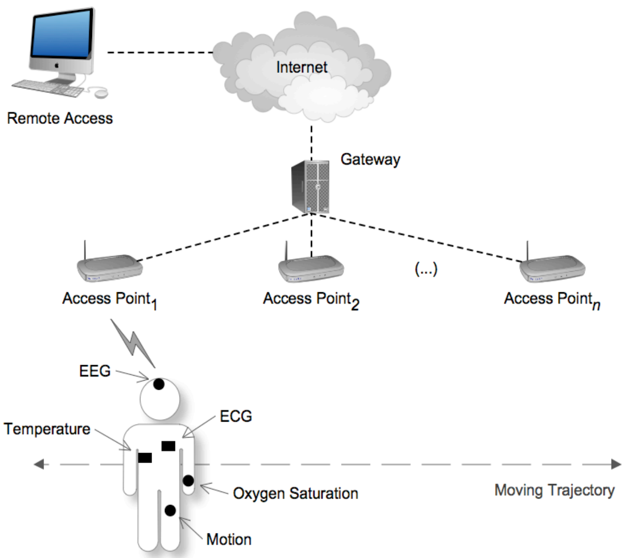

Fig. 1. Illustration of healthcare wireless sensor network architecture.

In HWSNs, the standard IEEE 802.15.4 is one of the most used wireless communication technologies [46]. This standard works in one of two operation modes, beacon-enable or non-beacon. The beacon-enable mode uses a super frame structure. This structure divides the time into four transmission periods, namely, beacon period, contention access period (CAP), contention free period (CFP), and inactive period. During the CAP, a clear channel assessment (CCA) is carried out before sending of the radio channel. If the channel is not clear there is a random waiting period before trying again. CCA is in line with beacon transmissions or receptions. The CFP is used for low latency communication required by some devices. CFP is based on guaranteed time slots (GTS). The nodes enter in sleep mode during the inactive period of the superframe. This mode avoids continuous communication due to the sleep period of the sensor nodes. Fig. 2 presents the structure of a superframe. In a non beacon-enable mode the IEEE 802.15.4 uses a carrier sense multiple access with collision avoidance (CSMA-CA). A test of the channel is performed by a CCA before sending. A waiting period of random time exists before a retransmission if the channel is not clear. This mode suppress the inactive period of the nodes, therefore it is possible to maintain continuous access to them [21].

Assuming (for these scenarios) that the sensor nodes tend to move within the same network domain, this survey only focuses on studying intra-mobility mechanisms.

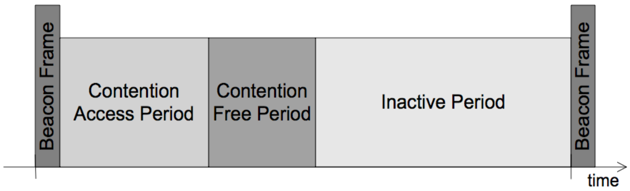

Fig. 2. Illustration of an IEEE 802.15.4 superframe structure.

III. Intra-Mobility in Healthcare Wireless Sensor Networks

A HWSN intends to cover individual hospital wards or even a whole hospital with network access. These areas can range from tens to hundreds of meters. Due to the limited coverage area of each AP in indoor environments, several APs should be scattered to cover the monitored zone. Intra-mobility is characterized by changing the point of attachment to the network but always within the same network domain (always keeping the same internet protocol (IP) address).

A. The Mobility Demand in HWSN

Improving the quality-of-life of patients is important to minimize the suffering of being hospitalized. Offering patients the possibility to walk around the ward knowing that the control of their health condition is not interrupted, is a significant improvement. Supporting this mobility is an important feature in HWSNs. Due to the use of several APs the HWSN should deal with nodes moving along different covered areas. Dealing with this behavior is not easy in HWSNs. If a node that losses contact with an AP is not already registered in a new one, it means that this node stops being monitored. This situation is not allowed in solutions that promise continuous and real-time monitoring, like HWSNs. To perform seamless transitions of nodes between different AP's coverage areas the definition and design of robust handover mechanisms is important. The fact that these nodes are powered by batteries (with a short life-time) means that the development of handover mechanisms should consider very low power in its operation [47].

B. Handover Requirements

Handover in WSNs is considered as the process of changing the registration from one AP to another when moving across their coverage area. This mechanism allows the inter-mobility process of nodes in WSNs. This process presents implications on the operating principles of these types of networks. For some reason if a node loses contact with an AP or takes long to register on a new one, the desirable continuous communication cannot be guaranteed. In HWSNs, the continuous communication with the mobile sensor nodes is performed through seamless handover mechanisms. These mechanisms should be designed taking into consideration the following features:

- The handover process should be fast and seamless. It should preserve the connection to the node during the whole process;

- Due to the energy wasted in handover processes, they should be minimized. Only if it is strictly necessary, should the handover be performed;
- After a successful handover, the changes of route to this node should be rapidly dispersed by the entire network infrastructure;
- The signaling process for a handover decision should be minimal. Few messages should the exchanged to maintain continuous communication with nodes.

All these features assume that sensor nodes operate in battery mode and, therefore, with energy constraints. These features keep in mind the optimization of nodes' lifetime and the principles of the HWSNs.

C. *Handover Decision Metrics*

In HWSNs, as above-mentioned, the continuous communication with nodes is very important. Then, when a node moves out of an AP's coverage area it should be already registered with a new one. The decision to perform a handover could be based on several parameters. A close monitoring of such parameters is important for better decision making. Furthermore, the mechanisms used to obtain these parameters can overload the network signaling and thereby reduce the lifetime of node batteries. Optimizing the number of monitored parameters and the mechanisms to evaluate them, can significantly improve the performance of HWSNs. The most monitored parameter used in these types of networks to evaluate handover decisions is the received signal strength indicator (RSSI). Then, the correlation of this parameter with others can improve the accuracy of the decision.

Next, the parameters that can be considered and evaluated to perform handover decisions are described.

Received signal strength indicator (RSSI) – as above-mentioned this is the most used parameter for handover decisions. It indicates the signal power of a message received by a node, typically measured in decibels (dB). Ideally, the variation of this value should be directly related to the distance between the sender and the receiver. But the value of this metric suffers from interference from the surrounding environment and, therefore, this relation is not linear in most situations. This behavior can reduce the accuracy of a decision based on the simple evaluation of this parameter. The evaluation of this value can be performed in two ways: (1) chose the best value and (2) the decision is based on a threshold value comparison. Now, each one of these approaches is described.

(1) Choose the best value. In this model, if a node moves to an overlapped coverage area of two or more APs, the one with the better RSSI value is the one that the node chooses to register. Due to the fluctuation of the RSSI values, this model could perform unnecessary handovers when a node is under several APs' coverage areas. Despite this undesirable behavior, this model is very simple to deploy and, if optimized, it is possible to reduce the signaling costs in the network when compared to the next approach.

(2) The decision is based on a threshold value comparison. To minimize the number of undesirable handovers performed by the previous model, this approach proposes the use of a threshold value to decide the right moment to find a new AP. If a node moves out of the registered AP's coverage area its RSSI value will decrease. If this value goes below a predefined threshold value the node stars searching for a new AP to register. This model needs close monitoring over the RSSI value. To support close monitoring, nodes and APs should exchange a large number of messages. Fig. 3 presents the use of a threshold value for a handover decision. When a sensor node moves from AP_1 to AP_2 coverage area, if the RSSI value with AP_1 drops below the predefined threshold value, then the sensor node starts searching for a new AP to register with.

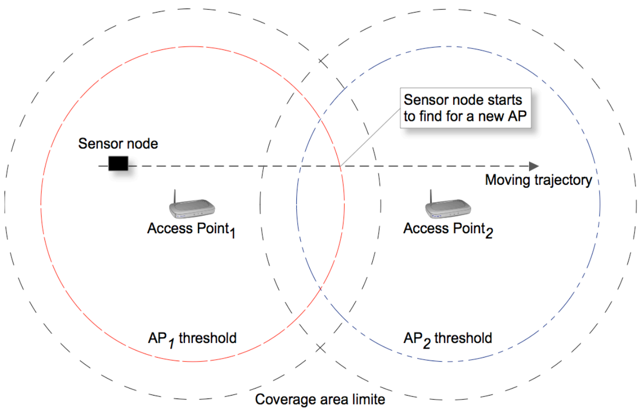

Fig. 3. Illustration of a handover decision when using a threshold value for RSSI evaluation.

The Link quality indicator (LQI) indicates the quality of the messages received by a sensor node or AP. This value should decrease when the distance between the sender and the receiver increases. However, the environment also affects this parameter like the RSSI. The use of this metric to evaluate a handover decision is preformed in the same way as described for the RSSI.

Velocity. This parameter is normally used in conjunction with others like RSSI or LQI. If the velocity is known the handover process may be adapted to its values. If a sensor node moves rapidly the threshold described for RSSI should be lower, since the time to perform a handover is smaller. On the other hand, if a sensor node moves slower, the RSSI threshold could be higher since there is more time to complete the handover. Nevertheless, knowing the velocity is difficult in small sensor nodes, which are geared to collecting human health parameters. In order to obtain this information the sensor nodes should incorporate additional technology which, therefore, increases the drain of the batteries to power it. Despite this handicap some handover algorithms combine the evaluation of this metric with others, to decide on changing the AP's attachment. In healthcare scenarios it seems that this parameter is not very important since it could be assumed that the speed of the patients is approximately the same all of the time. A human being moves at approximately 1 to 2 meters per second (m/s).

Movement direction. This could be an important parameter for a handover decision. If the direction of the movement is known, it is possible to predict the next AP in the route of the sensor node. That way, it could anticipate the search for that AP. When the next AP is reachable, the handover is performed for the node. This method is suitable in scenarios where sensor nodes use predefined trajectories without any additional computations. However, it is possible to estimate the direction of the movement using some technics in scenarios without predefined trajectories. Some of these technics are the angle of arrival (AoA) [48], the time of arrival (ToA) [49], and the triangulation/trilateration [50, 51].

Global position. This approach assumes the location knowledge, in real-time, of all the elements present in the network. To get this information the inclusion of global positioning systems (GPS) in sensor nodes is essential. When this approach is used, handover decisions are taken depending on sensor nodes' positions relatively to APs' positions. Nevertheless, this technology is very difficult to use in indoor scenarios because of the limitations in obtaining a satellite signal.

The next section presents a comprehensive review of several solutions that support intra-mobility of sensor nodes in WSNs.

IV. HANDOVER APPROACHES WITH INTRA-MOBILITY SUPPORT

In the past few years several solutions have emerged to support intra-mobility of nodes in WSNs, based on handover mechanisms. The most recent proposals that have contributed to the evolution on this research area are described below.

Zinon *et al.* in [52] proposes a solution for intra-mobility support in WSNs. This proposal is based on a new mobility management protocol for 6LoWPAN [53, 54] using a proxy-based procedure. As part of this investigation, a new intra-PAN mobility scheme is proposed. It works as follows: the current proxy agent (PA) measures the signal strength indicator (RSSI) received by mobile node (MN) communications. If this value goes below a predefined threshold, then, the current PA informs the other PAs to start hearing packets from this MN. In the case that a new PA receives a packet from the MN, then, the new PA composes a message that includes the RSSI value of the received packet from the MN, the MN address, and the network identification. This message is then sent to the current PA. When the current PA receives this message it verifies if the RSSI value is acceptable and if the identification is the same. If so, the current PA responds to the new PA with an acceptance confirmation for that MN. The new PA now informs the edge router (gateway) about the new route to reach this MN. The current PA also informs the MN about the new attachment point. This approach assumes the PAs are able to communicate with each other. The evaluation of this proposal was compared to an approach without using a proxy. It was demonstrated that the number of transmitted and received messages for signaling were much lower when using this proxy solution.

Jara *et al.* proposes a mobile IP-based protocol for wireless personal area networks in critical environments [55]. In this proposal the intra-mobility support is assured by an extension to IEEE 802.15.4 named GinMAC. This extension is also used by Zinon *et al.* in [56]. GinMAC monitors a set of parameters in real-time to maintain a good link quality to all the mobile nodes. These parameters are the RSSI to determine nodes´ movement and direction. This proposal considers that nodes can fall in one of two situations related with communication ability. In the first case the nodes are able to communicate while the second case assumes the nodes are in silent mode and, therefore, additional mechanisms are used. These mechanisms ensure movement detection and perform the handover within a predefined maximum time value. To deal with this problem the KEEP-ALIVE/NODE-ALIVE approach is used [57]. The registered AP sends a KEEP-ALIVE message at a regular time intervals. Then, the mobile node knows the exact time to expect this KEEP-ALIVE message. If a node does not receive the KEEP-ALIVE message, then, it sends a NODE-ALIVE message and waits for the return (acknowledge) by the AP. If the AP does not acknowledge, then, the node enters into scan mode for a new AP. To detect the possibility of network change a critical zone is defined. The critical zone is established between a predefined RSSI threshold and the disconnection point (rupture point). Two situations can occur as may be seen in Fig. 4 and Fig. 5. If the value of RSSI received is within the critical zone, the nodes immediately start searching for a new attachment point. This situation is depicted in Fig. 4. Another situation can occur when the value of RSSI is below the predefined threshold but, the next KEEP-ALIVE message is exchanged after the rupture point. This situation leads to a disconnected period of time for this node. Therefore, a NODE-ALIVE message is sent after the KEEP-ALIVE message. If the acknowledge is not received from the current attachment point then the node starts the scan mode to find another attachment point. This behavior is highlighted in Fig. 5.

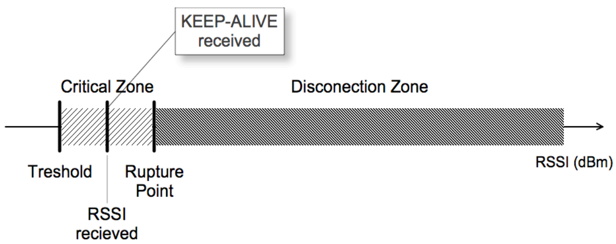

Fig. 4. GinMAC – RSSI received within the critical zone.

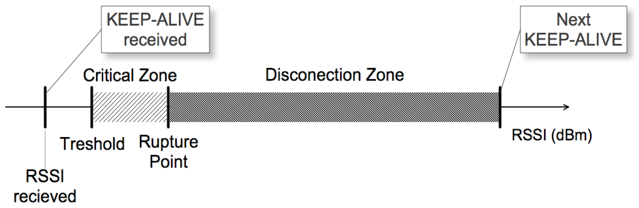

Fig. 5. GinMAC – RSSI received before critical zone.

An intra-PAN mobility support scheme for 6LoWPAN [58], called LoWMob, was proposed by Garbi *et al.* [59]. This scheme defines a model for multi-hop communication between mobile nodes (MNs) and a gateway (GW). To route the packets from/to MNs to/from the GW, static nodes (SNs) are used. SNs have energy constraint and therefore, they periodically change to sleep mode to save energy. Some nodes placed in the periphery of the personal area network (PAN), named border sensors (BSs), are used to detect MNs' movement. To support intra-mobility of MNs this proposal considers the sleep time of the SNs. So, if the current SN of a MN detects degradation on the link quality beyond a predefined threshold, it assumes the MN is moving out of its coverage range. Then, this SN needs to activate the next SN in the trajectory of this MN. To do this, knowledge about the direction of the movement is needed. This knowledge is obtained through the use of the angle of arrival (AoA) [48] method. When the MN crosses a predefined time-stamp in the direction of a new SN's coverage area, then the current SN awakens the new SN with a *new_node* message. This message contains the identification of the MN. Now, the new SN starts sending *hello_packet*s at time intervals. This new SN also sends a location update message to the GW. After the new SN detects the MN this SN sends a message to the previous SN to create a tunnel, used to send the possible incoming messages to the new location. If the new SN does not detect the MN within a time interval, then the node is considered lost. At this time, the new SN awakens all the surrounding SNs to search for the MN until it is found. This solution needs SNs to be able to communicate with each other. Therefore, the coverage area of SNs needs to reach the surrounding SNs. Jara *et al.* in [39, 60, 61] proposes a similar solution to support the mobility of sensors used to monitor patients in a hospital. Xiaonan *et al.* also use the same method (AoA) to find the movement direction of a MN [62].

In [63] Silva *et al.* proposes proxy-based mobility for WSNs. A similar proxy-based mobility solution is proposed in [64] to support multimedia data transferring in critical WSNs. In these proposals a proxy is used to perform the heavier tasks in intra-mobility support to reduce the energy consumption and the handoff time. In this deployment the concept of network of proxies (NoP) is used, consisting of several proxies all interconnected with a shared backbone. The local proxy is the proxy that takes care of a certain mobile node (MN). This proxy is responsible for the handoff management of all the nodes that it cares for. The proxy with the best link quality to a MN is chosen to be its local proxy. If a local proxy of an MN detects a deterioration in the link quality it notifies the neighboring proxies. These proxies reply with information on the link quality to this MN. Then, the local proxy choses the next local proxy for this MN based on the one that reports the best link quality.

Fotouhi *et al.* [38] proposes a handover procedure for the mobility support of mobile sensor nodes in WSNs. This proposal uses a set of metrics to evaluate the need for a handover. The metrics under evaluation on this proposal are RSSI level, velocity of the mobile sensor, number of hops to reach the AP, traffic load, energy level, and link quality value. To estimate the link quality based on all these metrics, it uses the fuzzy link quality estimator (F-LQE) described in [65]. The proposed handover procedure is performed in two phases. In phase one the need to handover or not is evaluated. The MNs periodically send probe messages to its registered AP. The APs reply with an acknowledgment message. The MNs decide to handover based on the evaluation of both – the RSSI average of the acknowledgment messages received from the registered APs and the velocity of MNs. But the procedure assumes the velocity of the MN may be unknown. If only the RSSI average is known, this value is compared to a predefined threshold. If the RSSI value drops below this threshold, the decision to handover is taken. On the other hand, if it is possible to obtain the velocity of the MN, the value of the average RSSI and the velocity of the MN are input to the fuzzy logic system. This system uses a set of rules to compute the final decision for handover or not. If the MN decides to handover in both situations (even velocity is either known or unknown) it moves into the second phase of the handover procedure. In the second phase of the procedure the MN starts sending probe messages at periodic time intervals to all the surrounding APs. This phase tries to select the best AP for this MN. After the probe messages are sent the MN starts receiving the acknowledgment messages from the APs in its vicinity. This phase of the procedure takes into account not only the RSSI value of the acknowledgment messages but also other AP-specific parameters such as traffic load, depth, and energy level. When the node collects all the information from the surrounding APs, it uses the F-LQE to estimate the best AP choice to register with.

Petajajarvi *et al.* [42] proposes a soft handover for WSNs based on 6LoWPAN (SH-WSN6). This proposal follows a different approach to support intra-mobility in WSNs. It allows the mobile sensor nodes (SN) to be registered with several attachment points (gateways - GWs) at the same time. The proposed architecture uses a remote resource directory (RD) that contains information on the resources and interface(s) used to reach each SNs in the WSN. GWs always send router advertisement (RA) messages at fixed time intervals. If a SN receives an RA it checks if it is already registered with this GW or not. If it is not registered the SN replies to the GW with a registration message.

TABLE I – Summary of a comparison between available intra-mobility solutions for WSNs.

	Continuous connection	**Multi-hop support**	**Movement type**	**Use of Backbone**	**Ping-Pong effect**	**Handover management**	**Used metrics**	**Unnecessary handover**	**Multicast intensive**
Zinon *et al.* [52]	yes	no	random	yes	yes	APs' side	RSSI	allowed	yes
GinMAC [55, 56]	no	no	random	no	yes	Nodes' side	RSSI and movement direction	allowed	no
LoWMOB [59]	no	yes	random	yes	yes	APs' side	RSSI and movement direction	allowed	no
Jara *et al.* [39, 60, 61]	no	yes	random	yes	yes	APs' side	RSSI and movement direction	allowed	no
Xiaonan *et al.* [62]	no	yes	random	yes	yes	APs' side	RSSI and movement direction	allowed	no
Silva *et al.* [63, 64]	no	yes	random	yes	yes	APs' side	LQI	allowed	yes (RA usage)
Fotouhi *et al.* [38]	Not guaranteed all the time		random	no	yes	Distributed (but essentially in node's side)	RSSI, velocity, number of hops to reach the AP, traffic load, energy level, and link quality value	avoided	yes (RA usage)
Petajajarvi *et al.* [42]	Dependent on the interval for RA messages	no	random	no	yes	Distributed	RA ratio	avoided	yes (RA usage)
Valenzuela *et al.* [66]	Dependent on the interval for DATA messages	no	random	no	no	Distributed (but essentially in node's side)	RSSI	allowed	no

At this time, the GW informs the RD about the new route to this SN. If this SN receives another RA from another GW it proceeds in the same way. At this point the SNs can be registered with more than one GW. To keep the registrations up-to-date, the SNs should know when a GW is out of range. This is known using a proposed connection quality comparison algorithm. This algorithm bases the decision to remove a registered GW on the comparison of the ratio of the RA received from the GWs in the neighborhood. For this decision the algorithm assumes that GWs send RA at the same rate. The removal of inaccessible GWs is important for keeping only valid routes to reach the SNs. This approach was evaluated in terms of handover latency and it has been proven as getting better results when compared to other solutions. However, this proposal considers that the time interval between the RA messages can influence the performance of the WSN in two aspects. If the time interval is too short it increases the traffic, and the processing in the network reduces the SNs lifetime. On the contrary, if the time interval is too long, the SNs can be inaccessible for long periods between RAs. It is important to mention that this solution is only suitable for single hop solutions.

In [66] Valenzuela *et al.* proposes an approach to support mobility for health monitoring at home using wearable sensors. This approach uses a sensor coordinator attached to a patient's body that is responsible for all the communications among the wearable sensor nodes and network APs. The handover mechanism used in this proposal works as follows. At first the coordinator sends a PING_MSG using all the 16 channels available in IEEE 802.15.4 standard. APs in the neighborhood acknowledge this message. Acknowledgment messages are used by the coordinator to collect the RSSI values to all nearby APs. After the collecting period the coordinator chooses to associate to the AP the one with the better RSSI. Now the coordinator starts to send health data to the network through the associated AP. Data messages are also used to maintain the RSSI value under control. If this value drops below a predefined threshold then the existence of any other sensor node controlled by that coordinator with a better RSSI value with the AP is verified. Then this sensor node is chosen to act as a temporary coordinator. If the RSSI value for all the sensor nodes controlled by a coordinator drop below the predefined threshold, then coordinator decides to handover and starts the scanning mode described at the beginning of this description again.

Table I summarizes the main characteristics of intra-mobility solutions for WSNs and the ability of each one to take into account these characteristics. A brief description of each considered characteristic is presented below.

1. Continuous communication. This characteristic refers to the ability of the sensor nodes to be accessible all the time even when moving.
2. Multi-hop support. This characteristic evaluates if the network allows sensor nodes to use neighboring sensor nodes to establish a path to the AP.
3. Movement type. This characteristic determines if the movement of the sensor nodes is predicted or random.
4. Use of backbone. If it is necessary that the APs be connected to each other using a backbone.
5. Ping-Pong effect. This feature is characterized by continuous message sending and receiving between the sensor nodes and the APs to assess whether they are still accessible to one another.
6. Handover management. The management of the handover procedure can be performed essentially from the APs' side, from the sensor nodes' side, or from both (distributed approach).
7. Used metrics. This characteristic defines the metrics used to evaluate the handover decision.
8. Unnecessary handovers. When a sensor node is under an overlapping APs' coverage area it may constantly change its registration point without needing to. This feature evaluates if the procedures avoid or not this behavior.
9. Multicast intensive. Some procedures use multicast messages to know which sensor nodes are within the APs' coverage areas. In these approaches the APs periodically send multicast router advertisement (RA) messages. All the sensor nodes within an AP's coverage area reply to the RA with an acknowledgment message.

V. Discussion and Analysis

As presented in Section III, intra-mobility in WSNs is supported by handover mechanisms. Several solutions were described considering different approaches for handover decisions. As confirmed by these solutions it is not easy to evaluate the exact moment to perform a handover. The definition of the exact time is important when ensuring a continuous connection to the sensor nodes. If this moment is optimistic it could introduce the existence of several undesirable handovers that causes much instability in the definition of a valid access to the sensor node. If this moment is too pessimistic, it could lead to periods of disconnection by the sensor nodes. Some of the proposed solutions tried to estimate the optimal moment to perform a handover by the evaluation of several parameters. To collect some of these parameters the sensor nodes must include additional hardware that contributes to higher energy consumption. Other parameters need an additional infrastructure to support their operability. Other parameters do not require additional infrastructures or hardware but they increase the computational effort (to get a decision) and, therefore, the waste of energy. Several solutions support multi-hop between sensor nodes and their points of attachment to the network (APs) [67]. These solutions seem to be suitable in scenarios where it is difficult to construct a network infrastructure. or if the number of APs is not able to cover the entire monitored region. The use of multi-hop solutions increases the signaling costs in the network to keep the routes to the sensor nodes updated. In scenarios with support to mobility of sensor nodes, the signaling costs greatly increase due to the constant variations in the sensor nodes' neighborhood.

All the described solutions use the standard IEEE 802.15.4. As above described this standard allows two operation modes, beacon-enable and non-beacon. The definition of handover mechanism should consider the implications of using each one of these modes. For example, the use of superframes in beacon-enable mode allows the sensor nodes to enter an inactive period for a period of time. Therefore, during this period the sensor nodes are not able to communicate so they are inaccessible. In the non-beacon mode the inactive period does not exist and, therefore, it is possible that sensor nodes are available at all times.

Some open issues and further research directions in intra-mobility support of sensors regarding the application of WSNs to healthcare scenarios are highlighted in the next section.

VI. Open Issues

In healthcare scenarios it is important that technology may be focused on the patients' quality-of-life. As described in Section II, the use of HWSNs improves patients' health monitoring. These technologies can be used for patient monitoring in both a real-time and continuous manner. When hospitalized, the patients should be autonomous and their mobility should be preserved whenever possible. That way the HWSNs should support this mobility and ensure continuous patient monitoring. This feature is not yet satisfactory in the available solutions. The mechanisms to support mobility in HWSNs should be light in terms of computational efforts, and use few signaling messages. In this perspective it is possible to reduce the usage of RA messages and multicast messages that strongly contribute to reducing the lifetime of the sensors and, consequently, the network.

Most of the described solutions use the Ping-Pong effect to maintain information about the real value of the received signal strength between the sensor nodes and the APs. This continuous exchange of messages contributes to the drain of the batteries and, therefore, to reduce the lifetime of sensors. HWSNs can be considered controlled environments, i.e., after a short period of time, nodes are well known by the infrastructure and it is uncommon to change these nodes (the nodes remain the same for long periods of time). Therefore, the advantages of this characteristic of HWSNs should be used to promote the mobility of sensor nodes. The idea considers that APs should be searching for a specific sensor instead of continuously monitoring the link quality or the RSSI between the sensor and the corresponding AP. If the AP finds this specific node and the node chooses to handover, then, the AP stops looking for it. If the sensor node moves into an overlapped coverage area of another AP, it starts to receive finding notifications from this new AP. At this time, the sensor node can decide to perform a handover or not. The decision can be based on the evaluation of the received signal strength value. If the new AP has a better value of received signal strength than the current one, then, the handover is performed. If not, the sensor node stays with the current AP.

Multi-hop support allows sensors to be able to communicate with APs through intermediate sensor nodes. The use of this approach increases the overhead signaling messages in the network and increases the computational processing effort of the sensors to manage the routes to their neighbors. Hospitals or wards can easily accommodate APs' infrastructure to cover the entire perimeter and, therefore, the use of single hop approaches with a star network topology.

As described in Section II the use of beacon-enable mode of the standard IEEE 802.15.4 allows inactive periods with inaccessibility to sensors during those periods of time. This situation is unsuitable for solutions that need continuous connection to sensors. One of the key principles of HWSNs is the continuous patient monitoring, so, sensors should be accessible at all times. In that way the use of non-beacon mode of the standard IEEE 802.15.4 should be considered for HWSNs applications.

VII. Conclusion

This paper surveyed the most recent literature on intra-mobility approaches for WSNs regarding their application in healthcare, and presented a detailed comprehensive analysis of it. The use of these technologies for hospitalized patient monitoring can be a key asset for health care promotion. The patients using body sensors can be monitored remotely through a HWSN. Furthermore, to give patients the possibility to move across an infirmary it is important that their sensors are kept under constant monitoring without interruption. After the characterization of HWSNs, the mobility issues in HWSNs supported by handover mechanisms were addressed. Handover mechanisms allow sensors to change their point of attachment to the network. Description and performance comparison of the most recent approaches for handover were considered. A brief discussion and analysis of the possible application of these proposals for health care scenarios was also presented. Finally, proposed open issues that can contribute to improving the performance of handover solutions when applied to hospitalized patients were highlighted.

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Chapter 3

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This chapter consists of the following article:

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Article

A New Wireless Biosensor for Intra-Vaginal Temperature Monitoring

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Abstract: Wireless Body Sensors for medical purposes offer valuable contributions to improve patients' healthcare, including diagnosis and/or therapeutics monitoring. Body temperature is a crucial parameter in healthcare diagnosis. In gynecology and obstetrics it is measured at the skin's surface, which is very influenced by the environment. This paper proposes a new intra-body sensor for long-term intra-vaginal temperature collection. The embedded IEEE 802.15.4 communication module allows the integration of this sensor in a Wireless Sensor Network (WSN) for remote data access and monitoring. We present the sensor architecture, the construction of the corresponding testbed, and its performance evaluation. This sensor may be used in different medical applications, including preterm labor prevention and fertility and ovulation period detection. The features of the constructed testbed were validated in laboratory tests verifying its accuracy and performance.

Keywords: e-health; IEEE 802.14.5; temperature; Wireless Body Sensor; Wireless Sensor Networks (WSN)

1. Introduction

Applications of sensor networks have evolved in many fields of investigation field due to their large applicability and development possibilities, especially in the Wireless Sensor Networks (WSN) area. Low power consumption and low data rates are the most important features for WSN applications. A WSN consists of a group of sensors that monitors some physical or environmental parameters. Within a WSN there exist three fundamental agents: the sensor node, the event, and the reporter. The sensor node captures the event parameter, reads, and sends the information to be studied by the reporter [1,2]. The reporter is the final user who will analyze and try to get solutions.

Nowadays, due to the technological evolution of e-health applications it is possible to have sensors of all the sizes and with numerous features, even sensors that can be placed inside (intra-body sensor) or outside (inter-body sensor) the human body, typically in contact with the skin. All these types of sensors must deal with many constraints on resources such as energy, memory, computational speed and bandwidth. Sensor networks could be applied in the medical environment, helping with the gathering of data for fast diagnoses and providing monitoring services [3]. The concept of "continuity care" has been increasingly adopted by the health community. These kinds of applications have experienced considerable growth, which contributes to the improvement of human life conditions and helps the progress of Medicine by improving disease diagnoses. In this context, a Body Sensor Network (BSN) is a sensor network for body applications. These sensor networks are applied in medical care and biofeedback, providing healthcare monitoring services [3]. The aim of BSNs is to provide continuous monitoring of patients in their natural physiological state so that transient but life threatening abnormalities can be detected or predicted. This network is composed of a sensing node with a processing unit and a limited power supply. If the sensing node is provided with a wireless transceiver we are then dealing with a WSN [2]. In Body Area Sensor Networks (BASNs), the signals collected by sensors relay them to the sink node and are connected to a central computer [4-6]. The communications between sensor nodes usually employ wireless technologies like Bluetooth and Zigbee [7] over IEEE 802.15.4, but the most used and best one for wearable health applications is the Zigbee communication protocol due to its lower power consumption [8,9].

Most studies based on body temperature control started initially as a tool to detect the female fertility period by observing the increase of body temperature, know as Basal Body Temperature (BBT), taken with a basal digital thermometer [3]. This method is very painful for females and does not guarantee the validity of the gathered data. Many reasons could account for the shortcomings of this method, like equipment accuracy, appropriate environment, and external temperature factors or misuse of the equipment.

All of these factors, plus the reduced number of biosensors available on the market to perform this task, justify our effort to develop and implement this type of biosensor. Another motivation stems from the planned close collaboration with a medical team, which provides great confidence for all stages of the development. This work will provide a great deal of temperature and acquisition time (day and hour) data that could be very useful for medical studies. A team of physicians from the Health Sciences Faculty, University of Beira Interior (Covilhã, Portugal) will study a possible correlation between the intra-vaginal temperature and different stages in the female reproductive process in order to prevent (or promote) pregnancy issues. This closed collaboration is an important contribution for the medical validation of accuracy, usability, efficiency, and system performance evaluation and validation.

This paper addresses BSN issues because all the monitored parameters are directly collected from the human body. The major objective of this paper is the proposal of a new intra-body sensor for e-health applications focusing on intra-vaginal temperature monitoring, and its corresponding prototyping, performance evaluation, and validation. A detailed design of a new intra-body sensor, specifically designed for temperature monitoring with wireless communication is presented, as well as construction of a testbed and the results obtained to validate the system.

The remainder of this paper is organized as follows. Section 2 analyzes the state of the art of available systems for human body temperature monitoring. Section 3 describes the essential requirements that are featured in the new sensor device and its prototype design. Section 4 focuses on the results achieved with the created testbed and Section 5 presents a discussion and our conclusions.

2. Related Work

The control of intra-vaginal temperature allows the detection of several symptomatic situations in women. One of the best known is the occurrence of ovulation and fertility periods. This womens' parameter could be used in studies of its variations and the evaluation of the effectiveness of gynecological therapeutics, to support to discovery of new contraceptive methods, in the prevention of pre-term labor and the detection of pregnancy contractions. The available solutions to evaluate the female temperature are almost all based on coetaneous temperature measurements. These body temperature values, as presented in [10], are highly dependent on the environmental temperature. Therefore, the use of women's core-body temperature values could improve the validation of monitoring systems in detection and control of the aforementioned womans' health situations. Over the years some systems to control and monitor women's body temperature for fertility assistance purposes have emerged.

As proven in the AMON project [11] the correlation between coetaneous temperature and core temperature is very difficult to establish. This situation led to the use of a temperature sensor not being recommended in this project for medical purposes. The DuoFertility project [12] proposed a commercial device for continuous measurement of body temperature. It comprised three modules: a temperature sensor which is placed in the armpit, a reader unit, and the corresponding application software. A reader unit module is used to gather all the measurements collected by the sensor. This module can be attached to a computer, and the third module is an application software to graphically visualize the temperature values. This system uses the coetaneous temperature to predict the timing of the fertility period. As mentioned above, these temperature values are very dependent on the environmental temperature, so the use of these values could lead to wrong interpretations.

In [13] a method for detecting and predicting the ovulation and the fertility period in female mammals is described. This method gathers information relating to the fertility of female mammals and comprises the following steps: (*i*) taking multiple temperature readings from the female mammal during an extended period; (*ii*) identifying and disregarding temperature readings having one or more characteristics of irrelevant or faulty data; (*iii*) obtaining one or several representative temperature values for the extended period; (*iv*) repeating steps (*i*) to (*iii*) over multiple extended periods; (*v*) analyzing the representative temperature values obtained over multiple extended periods indicative or predictive of ovulation in order to provide information related to the fertility of the female mammal. This method only describes a procedure for obtaining temperature measurements for fertility purposes in female mammals and not really an actual hardware system that allows this operation.

In [14] and [15] a sensor system for intra-vaginal temperature was presented. This system is based on a thermistor unit to be placed inside a woman's vagina. This unit was attached to a processing unit using a flexible cable. The processing unit was maintained outside the women's body. This system obtains good results in monitoring a woman's intra-vaginal temperature, but it is a uncomfortable to use due to the flexible cable used to interconnect the two parts of the system. Finally, Freundl *et al*. developed a new Quality Index (QI) and suggested a new method to test different cycle monitors or fertility prediction methods used to detect the fertility window for contraception [16].

The next section presents a biosensor system for intra-vaginal temperature collection. The biosensor was designed to be placed inside a woman's vagina near the cervix. Therefore, it collects core-body temperature instead of coetaneous temperature. It has also the ability to collect long-term intra-vaginal temperature measurements using a microSD (micro Secure Digital) card.

3. Methods

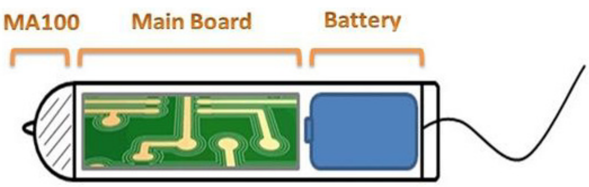
3.1. System Design

Due to the working location of the proposed sensor, it has to accomodate some anatomic limitations, namely, it should be easy to place inside the vagina and comfortable, because the main focus is to help prevent problems, not cause them. Following a medical recommendation it was determined that the sensor board and other peripherals had to fit in a container of about 60 mm × 18 mm in area, so a 30 mm × 16 mm size became the target for the main board with a microcontroller, a microSD card slot, a 2.4 GHz transceiver (IEEE 802.15.4), and a computer interface included. The use of a shape similar to a simple tampon seems to be a perfect choice. It is familiar to women, easy to use, anatomically perfect, and it has an appropriate size to accommodate all the features mentioned above.

The tampon-like shape presented in Figure 1 shows the conceptual design of the new proposed sensor. As may be seen, the thermistor is placed on the top of the container, the electronic circuit in the body of the container, and the battery in the tail. The enclosure must fulfill strict sanitary conditions so it needs to be properly closed and avoid in any way contact with the exterior. As known, the vagina is a humid place and no fluid should make contact with the electronic part to avoid electric conductivity. The electric current range used to power this circuit is not too high, but it is enough to cause damages to sensitive and tender skin like burns or others injuries. As concluded in [17], 2.4 GHz radiation has no effect on the human body, and therefore, wireless modules enabling 2.4 GHz technology could be used safely in the construction of intra-body sensors.

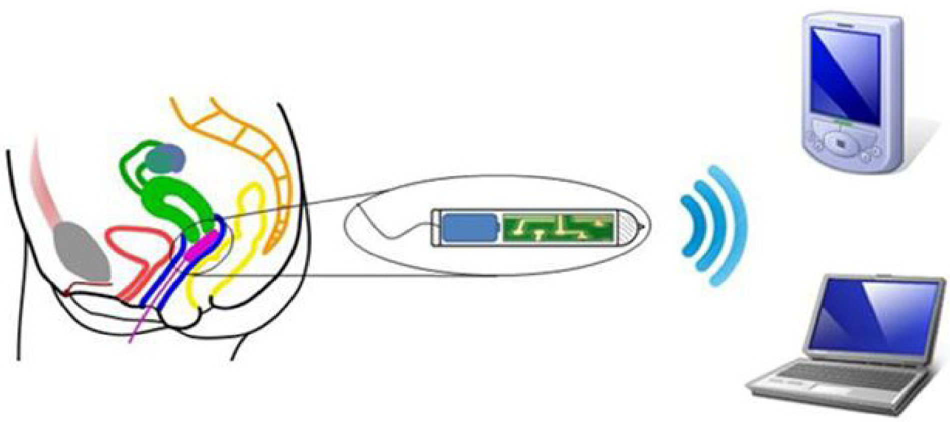
With the woman's comfort in mind, the sensor should operate when placed inside vagina. This feature avoids the need to take it out every time it is necessary to perform an operation to collect the measured temperature values. This feature will be implemented on this new sensor platform with the inclusion of a wireless communication module supporting the IEEE 802.15.4 standard. This feature also allows re-configuration of the sensor's mode of operation without any physical connection to the programming dock/station.

Figure 1. Conceptual design of the new intra-vaginal temperature monitoring sensor mote.



In WSNs it is expected that all nodes have a transceiver layer and a battery to achieve mobility, and spend most of the time in a low-power state, only waking up when readings and transmissions are required, as may be seen in Figure 2. The sensor is designed for collecting intra-body temperature measurements over long periods of time (e.g., during a complete menstrual cycle). This feature is guaranteed with the inclusion of a microSD slot for collection of a large amount of data. The sensor design includes a rechargeable battery with a regular voltage of 3.6 V and a capacity of 450 mAh, which can easily cover the power requirements of all the components for long periods of operation.

Figure 2. Illustration of the system architecture.



For temperature measurements a thermistor is included to measure the intra-vaginal temperature. The conception of this biosensor is only possible because of the use of Altium Designer, a software tool for schematic design. It can be used to design analog circuits, revise digital schematic diagrams for an existing PCB or to complete a hierarchical block design. Apart from its design functions, it also provides various built-in features for design verification and manufacturing processing. Altium Designer capture provides a component information system that allows one to identify, utilize and design with preferred parts.

3.2. Hardware Description

This section provides a detailed description of the features of the hardware components chosen to develop a single sensor board. Various components such as the Texas Instruments™

MSP430F2274 [18], Chipcon CC2420 [19], Antenova IMPEXA 2.4 GHz Antenna [20], TPS60100 [21] and the temperature sensor unit are described according to their contributions to the performance of the system.

The Texas Instruments™ MSP430F2*** [18] is one of the core components of the baseboard and its primary advantages are its extremely low power consumption during periods of inactivity and its proven history for medical sensing applications. The MSP430 is based upon the 16-Bit RISC CPU, peripherals and an adaptable clocking mechanism connected via a Von-Neumann memory address bus (MAB) and memory data bus (MDB). The architecture, combined with five low-power modes is optimized to achieve extended battery life in portable measurement applications. The device features a powerful 16-bit RISC CPU, 16-bit registers, and constant generators that contribute to maximum code efficiency. The digitally controlled oscillator (DCO) allows wake-up from low-power modes to active mode in less than 1 μs.

The CHIPCON CC2420 [19] is a single-chip 2.4 GHz IEEE 802.15.4 compliant RF transceiver designed for low-power and low-voltage wireless applications. The CC2420 includes a digital direct sequence spread spectrum base band modem providing a spreading gain of 9 dB and an effective data rate of 250 kbps. The CC2420 is a low-cost, highly integrated solution for robust wireless communication in the 2.4 GHz unlicensed ISM band.

To complete the IEEE 802.15.4 compliant wireless communication the Impexa 2.4 GHz SMD Antenna from ANTENOVA was the best choice. This antenna is intended for use with all kinds of 2.4 GHz applications such as in mobile phones, PDAs, PNDs, headsets, MP3s, laptops, PC-cards and sensors.

The voltage regulator chosen was the Texas Instruments TPS60100 [21]. The TPS60100 charge pump provides a regulated 3.3 V output from a 1.8 V to 3.6 V input. It delivers a maximum load current of 200 mA. Designed specifically for space-critical battery powered applications, the complete charge pump circuit requires only four external capacitors. The circuit can be optimized for highest efficiency at light loads or lowest output noise.

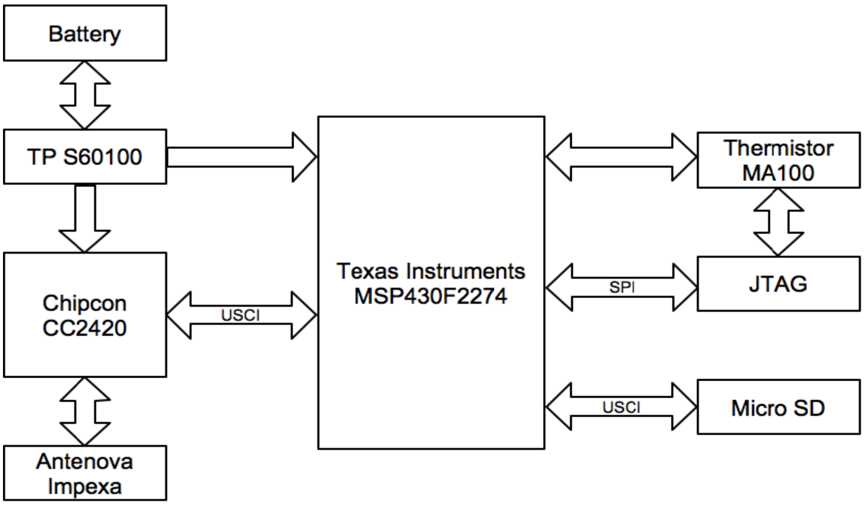
The thermistor electrical resistance can have a proportional (PTC type) or inverse variation (NTC type) with the increase of temperature. In the MA100 this variation is negative because it is a Negative Temperature Coefficient (NTC) type, so the resistance decreases with the increasing temperature. The NTC type of thermistor is more sensitive than other resistive sensors like Resistance Temperature Detectors (RTDs) or thermocouples, but being more sensitive means that it has a non-linear behavior and therefore a circuit is needed to adjust the exponential curve in a way that makes it approximately linear. Thermistors have a time constant which affects the time taken to make up 63% of the next temperature value. In power consumption the thermistor needs around 100 mA of current to start and power dissipation around 2 mW/°C. NTC Thermistors can have a stable acquisition in a range of −50 °C up to 150 °C.

The battery chosen is a lithium battery from GMBPower [22] measuring 15.5 mm × 13.5 mm, with a capacity of 450 mAh. This battery in particular was chosen due its circular shape and large capacity. As a regular battery, the nominal voltage will decrease as the battery is discharged. In order to provide a regular voltage of 3.3 V on the system, a voltage regulator is needed.

3.3. Testbed Architecture

This sensor node requires a small size and a long lifetime in order to satisfy a large number of applications [2]. The sensor node includes a small PCB with a microcontroller, a small rechargeable battery, an external memory card slot header, and a low power radio chip. Figure 3 presents the block diagram of the architecture used in the construction of the proposed sensor testbed.

Figure 3. Biosensor architecture block diagram.

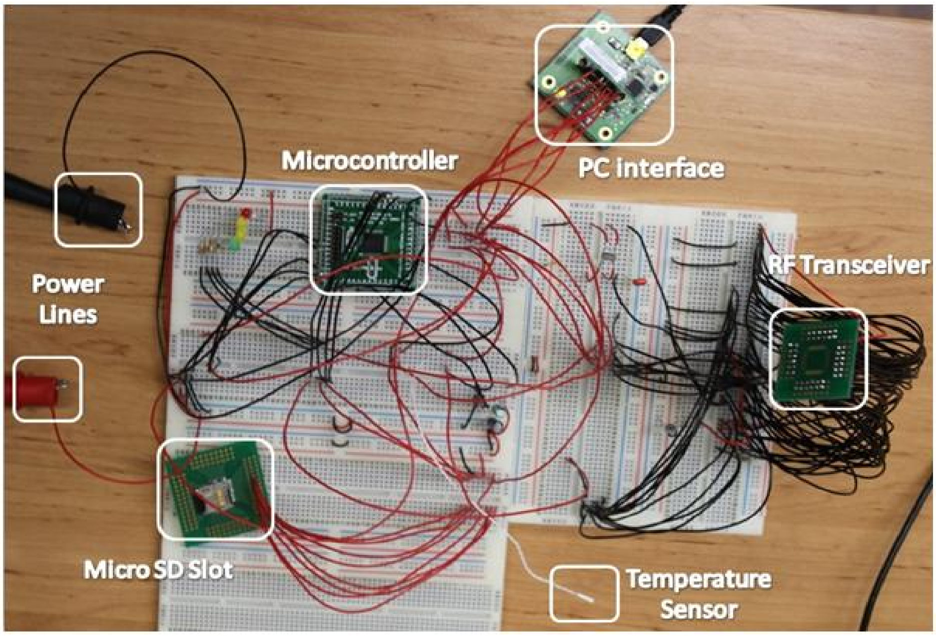


The microcontroller is the main element of the sensor because it influences the rest of the solution; a low cost microcontroller with low dynamic power consumption is essential. Thus, the Texas Instruments MSP430F1611 [23] was the best choice for this testbed because it is a component that was already used in previous work and it fulfills the most necessary requirements for the testbed construction. In addition the microcontroller selected with the intention of developing a miniaturized sensor prototype is the MSP430F2274, and both microcontrollers are similar, although the latter has small pin configuration (38 pins), with an optimal package style and does not need a thermal pad, which will ensure the possibility of miniaturization. In this specific software design, the MSP430 operates in two modes: ACTIVE Mode (270 µA at 1 MHz) and OFF Mode (RAM retention at 0.1 µA). The features presented allow the possibility of integrating new sensors in the future for other applications.

For communication purposes, the Chipcon CC2420 [19] is a true single-chip with 2.4 GHz IEEE 802.15.4 compliant RF transceiver, perfect for low power and low voltage wireless applications. This chip has a digital direct sequence spread spectrum baseband modem providing a gain of 9 dB and an effective data rate of 250 kbps. The antenna adopted seems to be a good option because it is intended for 2.4 GHz applications using Zigbee [6]. The size of the antenna is 6.1 mm × 3.9 mm × 1.1 mm, with a weight of 0.05 g.

For a sensor node, in many applications and usages, it is highly relevant to have big data storage. Then, the memory size becomes a limitation because the microcontroller only has 1Kbyte RAM and 32 Kbyte Flash memory, which is not enough to record continuous data during a week. The major advantage of the sensor is providing an external microSD card with up to 2 Gbytes of memory. As may be seen in Figure 4, a power supply was used to power the testbed but for the final prototype already tested lithium batteries will be used.

Figure 4. Physical testbed for performance evaluation and validation of the proposed temperature biosensor.



For the design of the temperature sensor, the MA100 [24] thermistor was chosen. It is an NTC Type MA Biomedical Chip thermistor developed by GE Industrial Sensing and exclusively used for biomedical applications. Its main features fulfill the requirements of this solution. Its sensitivity ranges from 0 °C to 50 °C, and its size is 0.762 × 9.52 mm. The size, shape, temperature ranges, and its approval for medical applications were the major reasons for this choice. To get more accurate temperature readings and taking into account its goal, the temperature sensor must be placed inside the female cervix, which is an ideal thermal source to reach the core body temperature. For this proposed architecture, the MA100 is embedded in the mote platform.

Using Zigbee [7] communication, temperature monitoring can be performed in real-time mode. The sensor platform also saves measured values in the embedded microSD card and can send them to external devices within the Zigbee range area. This wireless communication is also used to transfer all the data stored in the sensor's microSD card on demand.

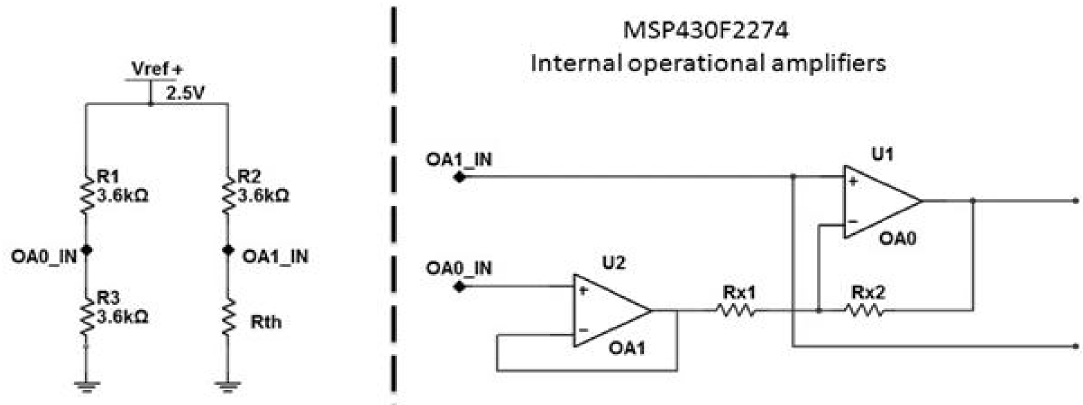
Another important feature of this solution is mobility. After mote activation and correct placement inside the vagina, the woman can move freely and do whatever she wants with comfort. After switching on the data collection (operation performed through remote commands), the sensor starts measuring and continuously storing data in the microSD card. The monitored woman only has to take the sensor out when the date advised by the physician has been reached. During a long monitoring period, the sensor need only be removed for battery recharge.

For a regular medical observation, a physician can use the mote to measure the current core temperature of a patient in his office with a real-time connection to the sensor, as described above. On the other hand, he/she can connect to the sensor directly and retrieve all collected data to his computer. In both cases a physician can monitor and control the evolution of this biological parameter by observing a graphical representation of the measured values.

3.4. Temperature Sensor Integration

The integration of the temperature sensor into the small biosensor board was definitely the biggest challenge for this work, not excluding the board design. As mentioned above, the MA100 thermistor was the chosen temperature sensor, and some additional electrical equipment must be attached to this type of sensor (NTC) to ensure the linear behavior of the resistance. For an NTC thermistor a Wheatstone bridge to measure resistors and an operational amplifier are normally used to ensure this linear behavior. Due to the features of the microcontroller used in this design it is not necessary to add differential amplifiers because the microcontroller already has two configurable operational amplifiers (Figure 5). The medical applications of this biosensor must support core-body temperature variations around 0.1 °C, therefore, the calibration of the biosensor's temperature sensor (MA100) is performed to a precision of 0.1 °C. The medical team that collaborates in this project validated this precision.

Figure 5. Thermistor signal acquisition circuit.



Equation (1) presents the relation between the two points on the Wheatstone bridge, which will generate the value of the differential tension on those two points (OAo_IN and OA1_IN). This value will be calculated internally by the microcontroller. It will be converted to a digital value on the available ADC10 line, considering the gain of the circuit amplifier. According to the proposed circuit some internal configurations need to be made to select the correct amplifier settings. As referred the microcontroller operational amplifiers can be configured with the OAFCx bits and to obtain a differential amplifier function it needs to be set to the "111" value. This mode allows internal routing of the OA signals for a two-opamp or three-opamp instrumentation amplifier. A two-opamp configuration with OA0 and OA1 will be used:

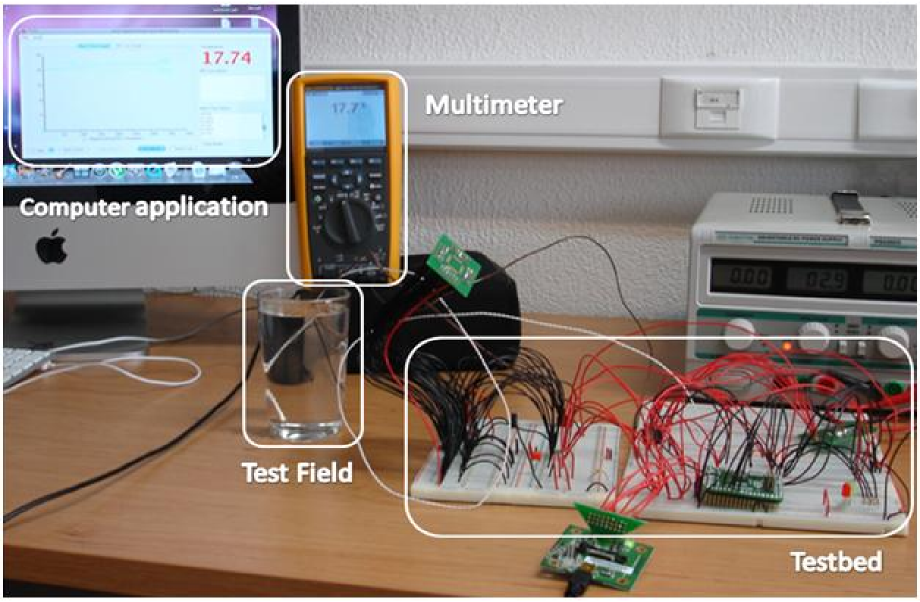
$$V_{ADC} = (\frac{R_{th}}{R_{th} + R_2})V_{ref+} - (\frac{R_3}{R_3 + R_1})V_{ref+} \quad (1)$$

The analysis of temperature measurements is performed in off-line mode. To ensure good results, it is vitally important to know the exact time when each temperature measurement is taken. The biosensor only has a local time clock, which starts on biosensor start up. This clock cannot act as the real global time clock. To associate each measurement with the right global time clock instant, when a start command is sent to the biosensor, computer also sends its clock and date time (assuming the computer clock is global clock synchronized).

4. Results Analysis

A temperature sensor was used to evaluate the proposed sensor design. Supported by the computer application presented in [15] temperature values were collected from the natural environment and from a glass of water. Several measurements were performed to make sure the sensor was recording the temperature values correctly or if any temperature variations were registered. To validate the sensor performance, the same measures were performed with a digital multi-function Fluke 289 [25] coupled with an 80BK-A thermocouple probe, as may be seen in Figure 6.

Figure 6. Experimental testbed for sensor validation of temperature measurements.



The tests were performed in permanent contact with water due to the intended real environment application of the body-sensor (inside the vagina). The temperature of the water used in these tests was the natural one of water gathered directly from the pipes. The thermocouple probe and the thermistor have been placed together inside the glass of water without any other interference. As shown in Figure 7 the water temperature slowly increased over time due to the higher temperature of the room. In real time, it was possible to verify the collected values through the testbed with the temperature calibrator (Fluke 289) and the current on the thermistor terminals.

Figure 7. Performance comparison between temperature values acquired with a thermopar and a thermistor inside a glass of water.

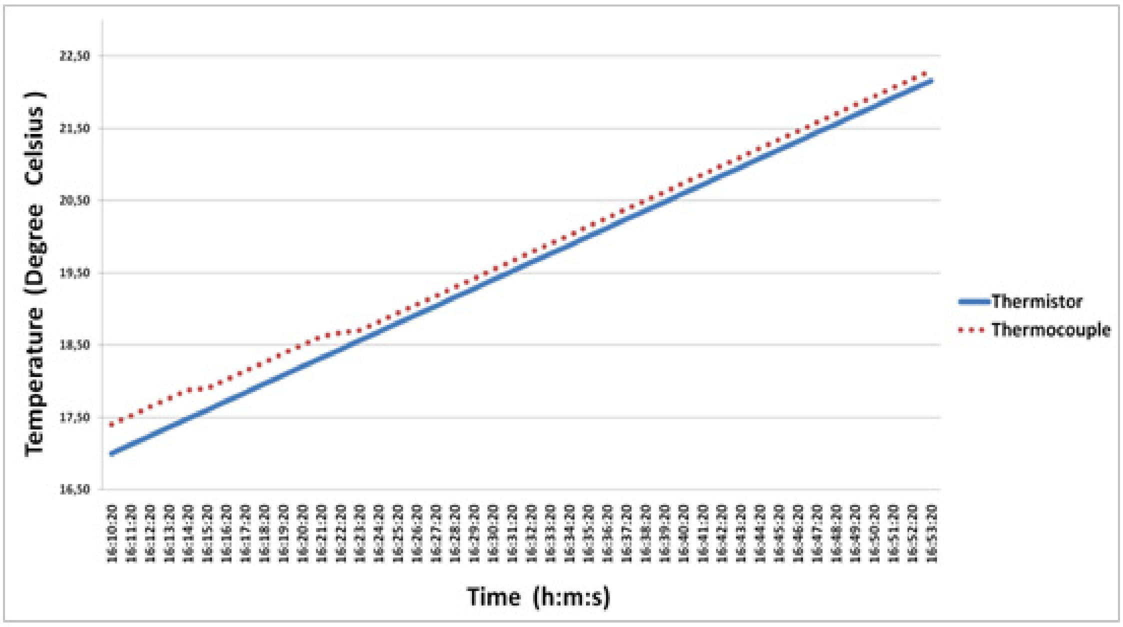
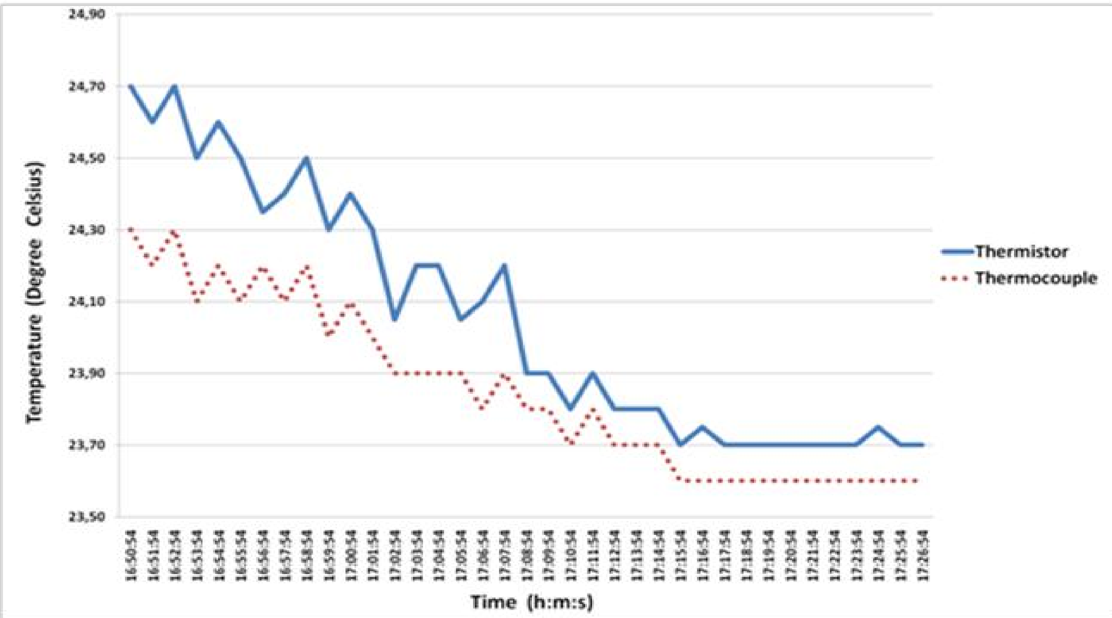


Figure 8. Performance comparison between temperature values acquired with a thermopar and a thermistor from a natural environment.



Another test was performed in order to confirm the accuracy of the temperature sensor, thus, a thermocouple probe and a thermistor have been used to record the ambient temperature of the room. Figure 8 presents the behavior of both temperature sensors and the difference between both temperature curves is clearly observed. In this test the thermistor presented a different behavior, having some difficulties in following or quickly reaching the same temperature value of the thermocouple probe. These variations registered by the thermistor could be due to the plastic enclosure that perhaps delays the quick response of the internal resistance in natural environments. According to these tests the behavior of the thermistor towards humidity in an environmental field and how it reacts to different variations of the temperature (increase/decrease) should be evaluated. These tests have contributed to the better calibration of the thermistor and allow us to conclude that thermistor is adequate for humidity fields.

5. Discussion and Conclusions

This paper presented the design of a new biosensor for e-health applications and the creation of a testbed to evaluate and validate the main functions of the new biosensor. This prototype was built to evaluate and validate the proposal, allowing the test of the several biosensor features. According to all the performed tests in a laboratory we can conclude that the temperature sensor acquires values with accuracy and it also collects and saves them on the microSD card correctly. Tests and performance comparisons were stressed in order to ensure the accuracy and usability of the biosensor. Those tests cannot be performed in (real) women due to health regulations/standards applicable to the use of electronic devices for human applications. According to the collected values it is possible to conclude that testbed was calibrated and measures the real environment temperature.

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Chapter 4

Toward Ubiquitous Mobility Solutions for Body Sensor Networks on HealthCare

This chapter consists of the following article:

Toward Ubiquitous Mobility Solutions for Body Sensor Networks on HealthCare

João M. L. P. Caldeira, Joel J. P. C. Rodrigues, and Pascal Lorenz

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Towards Ubiquitous Mobility Solutions for Body Sensor Networks on HealthCare

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Abstract— **The use of electronic health (eHealth) technologies in healthcare improves the quality of health services furnished to patients. The application of these technologies helps physicians and other health professionals to pursue early detection of abnormal status on patients' health. Body sensor networks (BSNs) are a type of wireless sensor networks (WSNs) aimed to be deployed on persons in order to collect physiological parameters for healthcare monitoring purposes. These BSNs are composed by several small sensors placed along patient's body, and capable to send (wirelessly) the collected health parameters to remote providers. BSNs need to operate every time and everywhere to transmit these important parameters to healthcare providers or automatic system to detect any anomaly in the patient health status. To provide this continuous monitoring of patients, it is mandatory to provide mobility support for the BSN so it can always be connected to some gateway to the Internet and therefore to back-end health providers. Several mechanisms with mobility support for mobile devices have been provided. However, the mobility support of a whole BSN has not been fully addressed. This paper overviews available handover mechanisms used for wireless sensors mobility and proposes a new ubiquitous mobility approach for BSNs in healthcare. A case study with this new handover mechanism developed for a hospital infirmary is presented and highlights the gain of performances of the proposed solution.**

Index Terms— **body sensors; e-Health; handover; mobility; wireless sensor networks.**

I. Introduction

New trends on healthcare technologies fall into the use of autonomous systems that allows the capturing and monitoring of physiological parameters any time and everywhere, also known as biofeedback. It may be performed by medical sensors installed on a patient body. This is achieved by associating communication boards with sensors allowing wireless communication among them and with a gateway to the Internet. Wireless sensor networks (WSNs) are used in many applications, from environment monitoring to human/animals biofeedback [1, 2]. Sensor nodes communicate among them and/or with a node called sink that acts as a gateway to a wired network. Thanks to the current standardization of Internet Protocol version 6 (IPv6) over Low-power Personal Area Networks (6LoWPANs), WSN nodes can communicate using IP protocol. This standard introduces an adaptation layer below IP, enabling the transmission of IPv6 datagrams over the standard IEEE 802.15.4

[3]. The adaptation layer performs header compression of IPv6 and transport layer headers, creating a new header comprised by a few bytes. Inside the LoWPAN, nodes do not need to decompress this header, since every node knows the compressed fields contents [4]. In that way, each network node should be IPv6-enabled and the interaction with them from/to outside is performed through a WSN Gateway [5, 6]. A gateway is placed at the edge of the network and can act as an interface between the WSN and the Internet (using IPv4 and/or IPv6). It allows a WSN to receive data from and to IPv6 hosts through 6LoWPAN. The application of this network architecture in healthcare (such as in a hospital infirmary) offers an efficient solution for patients monitoring in an autonomous and real-time way. In these scenarios it is important to let patients move around freely and without constraints, if possible for them (given their health conditions).

In WSNs, mobility may be categorized in two main topics stated as macro-mobility and micro-mobility. The movement of nodes between different network domains characterizes the macro-mobility approach while micro-mobility assumes that nodes move between different access points (APs) within the same network domain. The change of attachment point to a network is supported by handover mechanisms. It allows a node disconnection from an AP and connection to another one [7]. These associations and disassociations operate at the OSI model (open systems interconnection) Layer 2 (L2) and, thus, the IP address from the node does not change between different APs' attachments. Furthermore, handover mechanisms verify if AP changing is required (because the signal strength or the link quality is poor) and, if so, they handle this changing. Thus, handover mechanisms intend to endow these systems with ubiquitous features and enable continuous access, making mobility management transparent to patients, applying WSN mobility support for body sensor networks (BSNs). Using these approaches, patients do not need to worry about their movements' boundaries because the system is capable to support mobility while performs monitoring continuously. Body sensors carried by patients are used to gather different physiological or biological parameters continuously, as required by several pathologies and therapeutics control. The most common body sensors are the following: body temperature, heart rate, pulse oximeter oxygen saturation (SPo2), blood pressure, electrocardiogram (ECG), movement (with accelerometers), and electroencephalogram (EEG). In this context, BSNs with mobility support, provided by handover mechanisms, becomes a reliable solution to be applied in healthcare scenarios, like hospitals, nursing homes, and elderly or disabled persons homes [8].

In mobility scenarios, if a node loses contact with its corresponding AP, it is one of the most problematic issues. This behavior occurs because the system is not aware for a valid period of time that node can be out of the communication range of its current registered AP. The most recent approaches to solve this problem use some link quality metrics to evaluate the handover needed. These approaches are very heavy for the nodes' batteries due to the continuous messages exchanges to collect and analyze the link quality metrics. Based on a study of the available solutions in the literature, this paper proposes a new solution for controlled environments (like hospitals, patients homes, nursing homes, and others) where used nodes tend to be the same for long time. This approach tries to minimize the messages exchanged between nodes and their APs by using an historic cache placed in the APs' side. This historic cache gathers information from all the nodes that have been registered once to this AP. The AP always tries to reconnect with these nodes by sending them reconnection messages. This approach seams to be more efficient in terms of nodes' batteries lifetime due to the elimination of continuous messages exchanges to evaluate the link state between nodes and APs in their range. Then, this paper focuses on simple and reliable handover mechanisms used to support sensors mobility for health monitoring of hospitalized patients. This study assumes micro-mobility approaches, involving handover mechanisms, characterized by changing the point of attachment (to AP) within a network domain. Other details related with global/Internet connectivity with sensor nodes are not considered in the paper.

The rest of the paper is organized as follows. Section II describes the most relevant mobility approaches available in the literature for BSNs/WSNs focused on handover/handoff technics. Section III details a proposed ubiquitous mobility approach for

BSNs in healthcare scenarios while a case study with the new handover approach developed for a hospital infirmary is presented in Section IV. Finally, Section V concludes the paper and points directions for further research works.

II. Enabling Body Sensors Mobility in Healthcare Scenarios

Recent approaches to support sensors' mobility in WSNs and body sensor networks (BSNs) are reviewed. It is assumed that available contributions for WSNs can be integrally transferred to BSNs. A routing protocol for WSNs with mobility support evaluated in a real testbed using autonomous mobile robots is proposed in [9]. This protocol offers a beacon based scheduling for registration process between wireless routers and mobile nodes. The nodes based their registration on a wireless router by receiving from it beacon frames or data packets in a pre-defined time interval. If none of these packets arrived, then, the mobile node assumes that there was a link failure. Next, the mobile node tries to find a new wireless router with best link quality indicator (LQI). LQI is used to evaluate the quality of the received packets. In this solution, nodes become inaccessible during the handover process once it only starts when the connection is lost with the current router.

A mobile protocol for hospital WSNs is presented in [10]. This protocol supports intra-WSN mobility exploiting the elements in the proposed architecture, such as sink nodes and gateways. Each hospital room has a local gateway that ensures the connection to the Internet and other local room's gateways trough the network backbone. This proposal assumes that each node has a base network (home network) and could move into other networks, called visited networks. When a node starts moving out of a network covered area it detects that its link quality with the current network goes beyond a predefined threshold. The visited networks periodically sends beacon messages. Thus, when this node enters into a visited network it receives the beacon message and the needed information to communicate with the visited network gateway. Any new node in the covered area must receive the beacon messages. It seems these messages must be sent in a multicast/broadcast manner. Therefore, nodes that are currently registered in this network also receive and process these messages unnecessarily, decreasing its available energy.

In medical-WSN applications, nodes disconnection is not allowed, even, when the nodes could move freely. Fotouhi *et al*. [11] present a handoff procedure for mobility support in WSNs that can be easily migrated for BSNs. In this proposal, several parameters are used to determine the time for handoff, but the most significant are the received signal strength (RSS) (link quality) and the node velocity. They assume that velocity may be unknown, so the procedure should be only based on a RSS decision. If the RSS connection with the current AP is below a defined threshold, then, the handoff mechanism is initiated. To acknowledge the received signal strength between a node and the AP, the node periodically sends probe requests that, in turn, are acknowledged by the AP. If the acknowledge is not received the node starts the handoff procedure immediately. If the node receives the acknowledgement, then calculates the average of last received RSS values and, if the values are under the threshold, it starts the handoff procedure. This approach needs a continuous exchange of probe/acknowledge messages between the mobile node and the corresponding AP to verify the quality of the link and, based on this analysis, it decides for handoff. This continuous messages exchange penalizes the network in terms of energy consumption.

In [12], the authors propose a WSN mobile solution for 6LoWPAN networks. This paper addresses issues related with inter-PAN (Personal Area Network) mobility but they also propose a solution for a proxy change of mobile nodes inside the same PAN. This mechanism is based on the evaluation of the received signal strength indicator (RSSI) value of messages exchanged between the mobile node and the current proxy agent. If the RSSI value goes below a predefined threshold the current proxy agent informs the other proxy agent to start hearing for packets from the mobile node. If the new proxy receives a packet from this node, then, the association is performed with this new proxy agent. Afterwards, the new proxy agent sends a proxy confirmation for the mobile node to the old one.

In WSNs, the most used metric to decide the time for proceeding with handover is the quality of the link between the mobile node and the attached access point. In order to know this value, there are frequent messages exchanged between these two network elements. The power consumption to process all these messages at mobile nodes penalizes dramatically their lifetime. In real-time monitoring systems it is important a continuous access to the sensor nodes. As described in some of the above-presented approaches this requirement is not supported. Next, a new mobility mechanism for WSNs is proposed for reaching a more efficient real-time connectivity and reliable approach for being applied on healthcare and biofeedback solutions. In these eHealth scenarios it is important keeping patients always under monitoring, to control their overall health status. The values collected by patient body sensors allow this control. This work is not only based on collecting these values remotely over a wireless body sensor network (WBSN) but also on how to achieve this desire with mobile support of the patient sensors.

III. Ubiquitous Mobility Approach for BSNs

Mobility support in BSNs (and WSNs as well) is a great challenge and increases the applicability of these technologies. The major applications of these networks only assume static nodes and the used protocols are based on this assumption. To achieve a continuous connectivity with body nodes with mobility support, it is important to develop self-configuration (handover) mechanisms that can handle with link transitions between different APs. These handover mechanisms allow the ubiquity in BSNs/WSNs, once they must work properly in a self-mode without human intervention. The handover process must ensure continuous nodes connectivity if there is an AP available to cover the area of these nodes. If not, the handover process should provide a fast and light AP attachment when a new one becomes available.

The BSN nodes used in these scenarios are very tiny and, consequently, limited in terms of resources. Their typical constitution includes a small processor, a power source (normally a battery), a memory unit, input/output ports, and a wireless communication transceiver (IEEE 802.15.4 compliant). Usually, the batteries used to power up these nodes are the drawback of these systems. The nodes only depend on these units to keep alive. Due to the small size of the nodes the time-to-live of these batteries is limited from a couple of hours to a couple of days, depending on the operating mode. Sending and receiving messages over the air is one of the most energy consumption tasks for the nodes. Due to this, a light handover mechanism is more convenient in terms of messages exchange.

In scenarios like hospitals, the system architecture assumes a single hop communication using a star network topology and several APs (with a coverage range of about 5 to 10 meters) should be used to cover the monitoring area, all within the same network domain. The system uses a gateway to establish the communication between the BSN and the Internet. Figure 1 presents this system architecture.

Most of the handover procedures based the decision to search another AP on the evaluation of certain parameters that can be organized in two groups, i.e., the movement parameters and the communication parameters. Typically, the movement parameters consider the node position, velocity, and movement direction. However, these parameters are difficult to obtain in such tiny nodes created to gather physiological parameters. Typically, proposed solutions that evaluate these parameters use dedicated devices (such as Global Positioning System - GPS) and/or other technologies to collect these data [13, 14], such as radio-frequency identification (RFID). These solutions try to predict the handover requirement, knowing the global position of the node, its velocity, and movement direction. The second group uses communication parameters to manage the requirements for handover procedures. As above-mentioned in Section II, the wireless link between two devices can be evaluated by two metrics, the RSSI and the LQI. Ongoing works try to estimate the better metric to evaluate the quality of a wireless link [15]. Although these two parameters offer different contributes for quality estimation of wireless links, they are used in the same way for decision of a handover procedure. The RSSI or LQI are always under continuous monitoring by the mobile node and, if they fall beyond a predefined threshold, the mobile node starts the process to find another AP [11, 12].

The above-described approaches, based on movement and communication parameters, assume a continuous message exchange between sensor nodes and APs to realize the time to start a handover procedure. Assuming that nodes transmit data in asynchronous mode, and possibly with large intervals of time, they must continuously exchange messages with the AP only to ensure the current AP remains accessible. Figure 1 illustrates the operating principle of a handover mechanism. When a node loses its connection with an AP, it starts immediately the mechanisms to find another one to attach. As may be seen in this figure, the sensor node S_1 follows the trajectory from the left inside to the right inside, performing handover from the AP_1 to the AP_2.

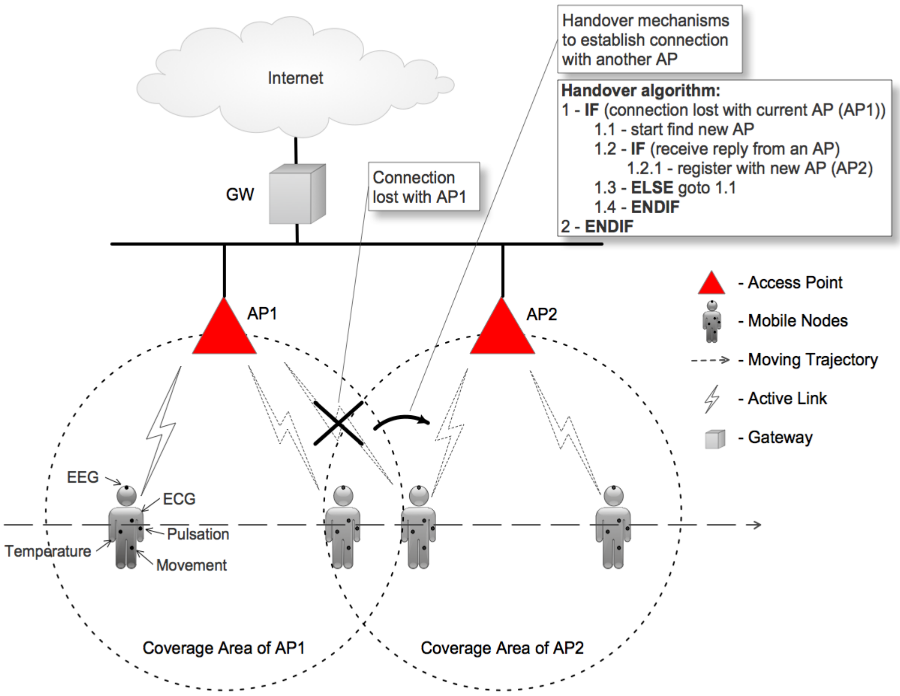


Figure 1 – Illustration of the system architecture and operating principles of handover mechanisms.

The next section presents a case study with a detailed description of a handover procedure that optimizes the nodes batteries lifetime in opposition to the APs energy consumption. This choice assumes that APs are powered with external sources and do not have any energy constraints in terms of lifetime.

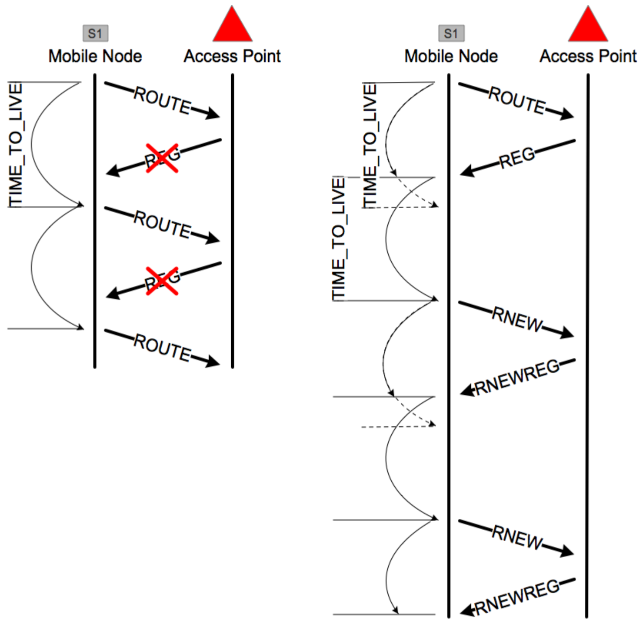
IV. CASE STUDY: A DISTRIBUTED HANDOVER PROCEDURE TO SUPPORT BODY SENSORS MOBILITY AND CONTINUOUS ACCESS

This case study is based on a BSN for biofeedback monitoring in a hospital infirmary. It uses the system architecture presented in the Figure 1 with IPv6 over 6LoWPAN for communication support between mobile sensor nodes and APs. In this scenario, all the nodes tend to be the same and should be the same nodes for a long time. Then, most likely they already have been registered in all the APs that cover the monitored area. The proposed mobility support approach tries to optimize the continuous access to mobile nodes that are already known by the APs and minimize the register process of nodes that came into an AP covering a geographic area for the first time.

The presented handover mechanism uses a distributed approach. Therefore, the problem can be studied considering two different methodologies. One addresses the mobile node side and the other is performed at the APs side. In the following sub-sections, these two procedures are described and their contribution to the overall system solution with ubiquitous mobility support for WSNs/BSNs is evaluated.

A. Mobile Node Request

When a node tries to find a new AP at the first time, it sends multicast ROUTE messages at TIME_TO_LIVE time intervals waiting for a response from an AP. This behavior also occurs in two additional situations: *i*) when a node lost connection with its current AP and needs to find a new one or *ii*) when a node goes to an area without AP coverage. This process is illustrated in Figure 2. As may be seen, a node sends a multicast ROUTE message to the AP addresses list. Then, the node waits a TIME_TO_LIVE to receive a REG message from any AP in the covered area. If the REG message does not arrive in this TIME_TO_LIVE, the node sends another multicast ROUTE message. This behavior is illustrated in the Figure 2 a). Once ROUTE messages are sent to the multicast group of the APs of this network and a node is within multiple APs coverage, then several APs could respond with REG messages. Due this, the node must choose only one AP to register. It chooses the AP with best link quality using the LQI parameter. After a successful registration, the node exchange RNEW messages with registered AP (using unicast) every TIME_TO_LIVE, waiting for a REG message from the registered AP. This procedure is illustrated in the Figure 2 b) diagram. If a REG message is not received inside the TIME_TO_LIVE time interval, the node starts again sending ROUTE messages (Figure 2 a)) in order to register in a new AP, and the process continues along the time.



a) **b)**

Figure 2 – Illustration of messages exchanged between a node and an AP under a handover procedure with a) registration message from the AP not received in the TIME_TO_LIVE time interval, and b) a successful registration process with an AP.

B. Access Point Side

The APs store the information of previous registered nodes in a historic cache, even after losing a connection with them. This information is then used to try to contact each mobile node, in the historic cache, by sending unicast FIND messages to each node (with a frequency of REPEAT_TIMER). If a node is reached, then the node verifies if the LQI of the last message exchanged with the current AP is greater than the one received now. If not, it stays registered with the current AP. If so, it changes its registration to the new AP returning a FINDACK message. At this point, the node sends also an unregistered message (BREAK) to the current AP. The current AP, upon receiving an unregistered message (BREAK), moves the node information from the registered list to the historic cache. This process is detailed in Figure 3 and 4. Figure 3 illustrates the process of no node association with the new AP while Figure 4 shows the process of changing the node registration to the new AP.

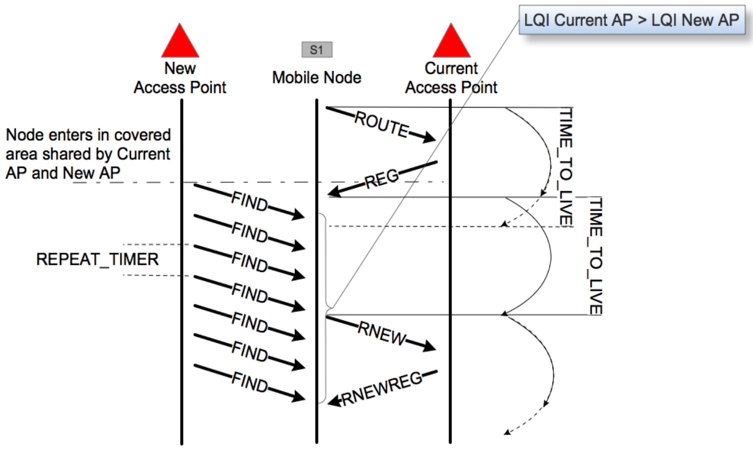


Figure 3 – Handover mechanism when the LQI of the current AP is greater then LQI of the new AP, once a node enters in a shared covered area.

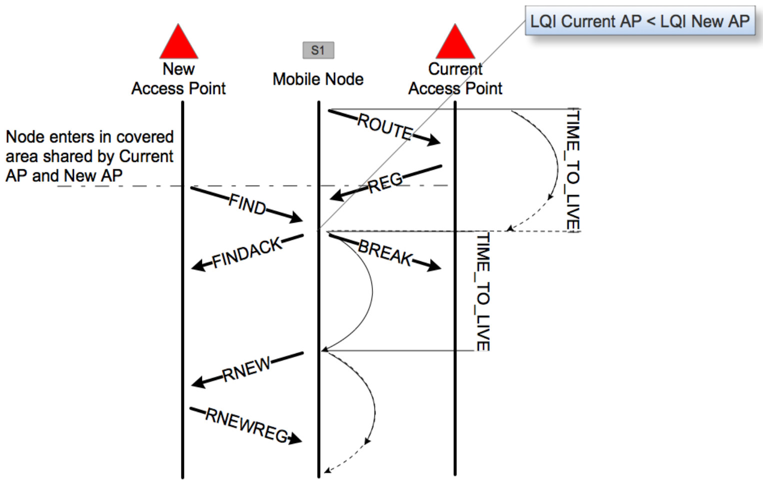


Figure 4 – Handover mechanism when LQI of current AP is lower them LQI of new AP, once a node enters in a shared covered area.

If the unregistered (BREAK) message from the node never reaches the current AP because of the node movement, then two active registers are valid for that node, one through the current AP and another through the new AP. In this case, when the node is contacted from outside the sensor network, the gateway should analyze the timestamps of the active registrations in all the APs for that node and select the one with the most recent registration timestamp. To avoid overflow problems with the increasing of the historic cache, this should be maintained by the APs. If no more space available for new entries the oldest ones are removed.

C. Node versus Access Point Handover

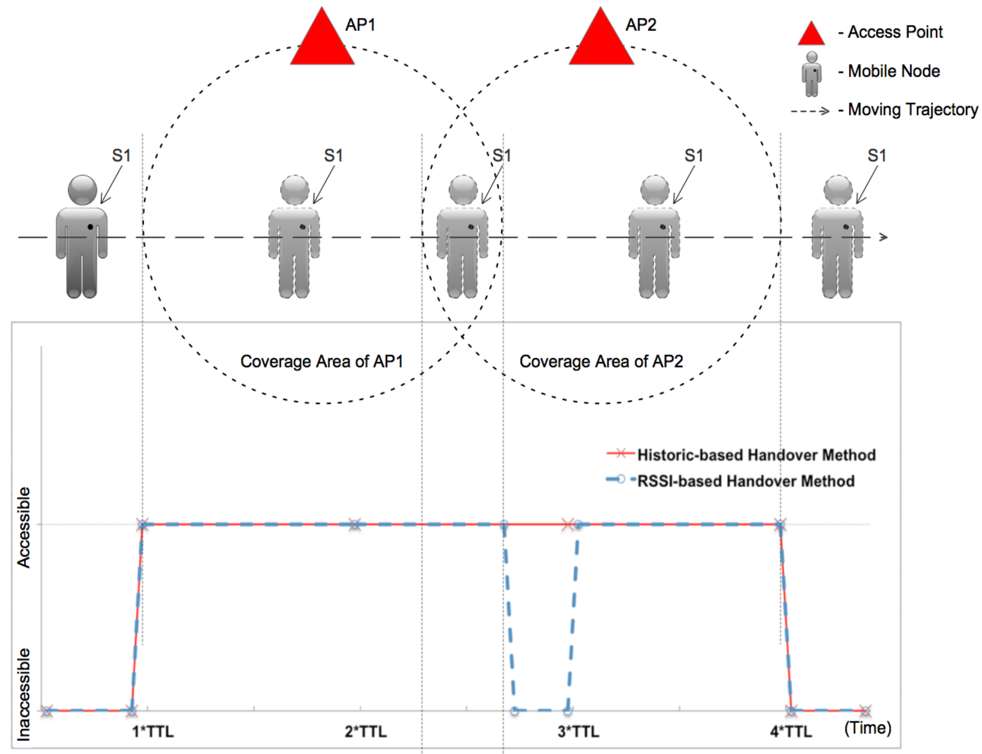
The advantage of the proposed approach comes from the fact that it does not require continuous messages exchange between a mobile node and the current registered AP to detect the connection lost in order to start the handover process. This approach is optimized for nodes that already had a valid register in the APs. Thus, the handover procedure performed by the APs should be prioritized regarding the one running at the sensor nodes. This decision also privileges the use of unicast communications instead of multicast, which has a greatest impact in nodes energy consumption.

The definition of time intervals has a real implication in the effectiveness of this approach. The node's handover mechanism depends on the TIME_TO_LIVE interval to resent ROUTE messages in order to find an AP. Then, APs mechanisms should be prioritized and the nodes mechanism is only needed when a node moves into a never registered AP covered area or if, for some reason, the RNEWREG message from the current AP is not received. The TIME_TO_LIVE should be long enough to prevent these situations. On the other hand, once APs do not have energy constraints and the handover procedure should be as fast as possible, the REPEAT_TIMER should be very short.

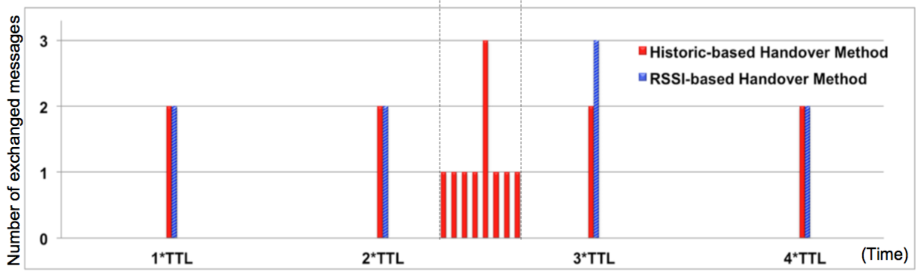
D. Results Analysis

To evaluate the performance of the proposed handover solution a case study was used. This study was performed by simulation using the OMNet++ tool. The evaluation study focused on the continuous access to a mobile node in the coverage area and the cost of messages exchanged between a mobile node and the APs to prevent losing connection. This analysis was based on the comparison of the historic-based handover method (HHM), proposed in this paper, and an RSSI-based handover method (RHM) [11] previously described.

Figure 5 illustrates the mobility scenario used in the study. The scenario considers a mobile node (S_1) that travels across two APs' coverage areas. It is assumed the node is already in the historic list of the APs. At the first configuration, the nodes travel with constant velocity and it is used a TIME_TO_LIVE (TTL) that was three times bigger than the interception area of the two APs' coverage areas. In Figure 5 a) the accessibility to the node when it moves from the left to the right is presented. It is possible to observe that mobile node is always accessible using the HHM due to the FIND mechanism (described in Figure 33 and 4) when it passed the interception area. When the RHM approach is used, the node losses its accessibility when it moves out of AP_1 coverage area until the next TTL timer (*3*TTL*). This situation occurs because the RSSI value in *2*TTL* was above the threshold and the next analysis only was performed in *3*TTL*. In this approach, the mobile node only realize that because it was out of coverage area at *3*TTL* and only, at this time, it starts the handover procedure. In terms of messages exchanged, all over the simulation process it is presented in Figure 5 b). When the nodes were out of APs' coverage areas they send ROUTE messages. When the nodes were covered by the registered AP two messages were exchanged (RNEW and RNEWREG). When a node enters the intersection area, using the HHM, it starts to receive FIND messages from the AP_2. Then, when the LQI of AP_2 becomes greater than the LQI whit AP_1 the system performs the handover procedure by exchanging FIND message from AP_2 and the node retrieves with FINDACK and BREAK messages to the AP_1. Using RHP at *3*TTL*, the node sent a RNEW message to AP_1 with no response and after sending the ROUTE message that was acknowledged by AP_2, it performs the handover for the node. In this scenario, the total number of exchanged messages in HHM was greater (18 messages) than in RHM (9 messages). However, in other hand, in RHM it has an inaccessible time interval that is not allowed in continuous monitoring WSNs.



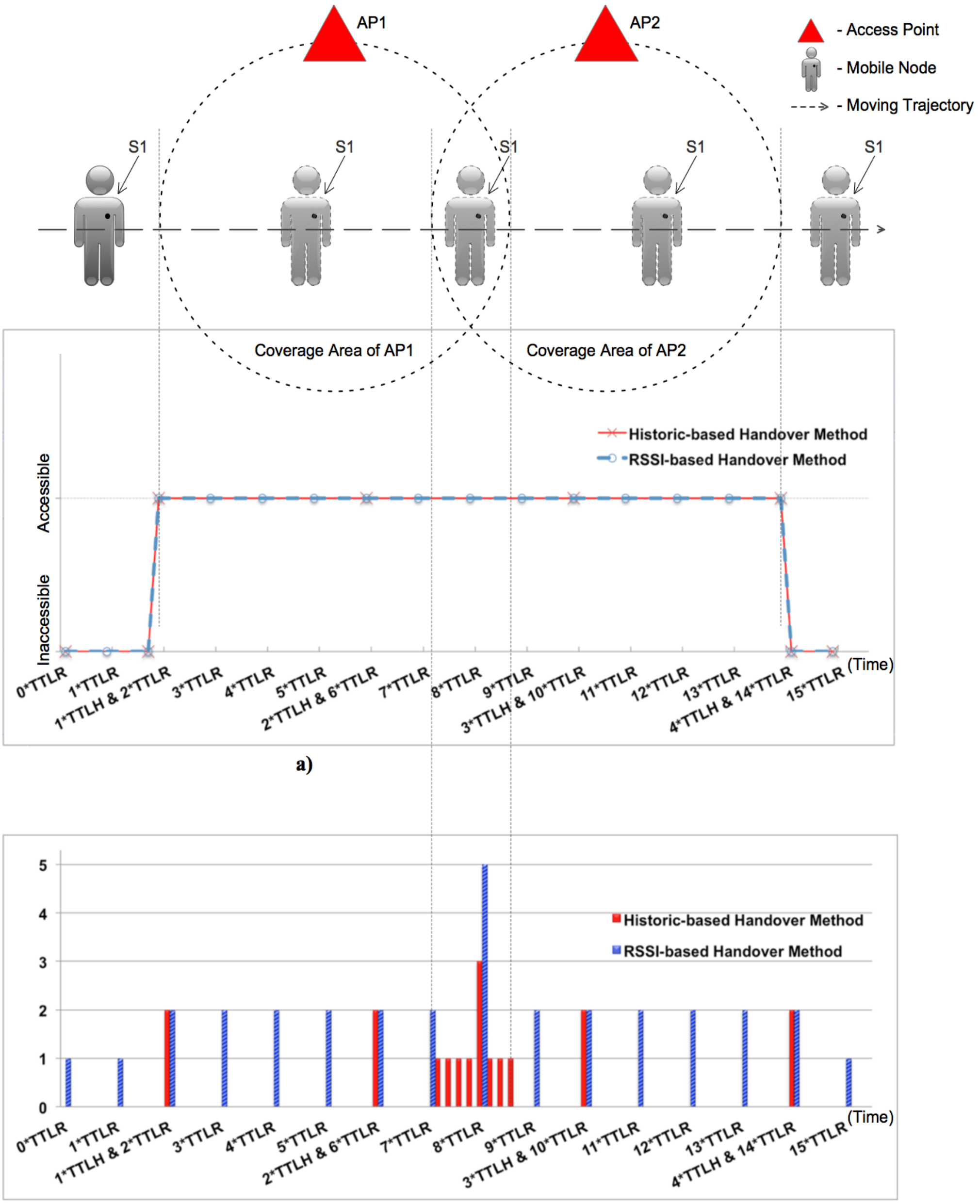
a)



b)

Figure 5 – Performance evaluation of the proposed Historic-based Handover Method (HHM) and RSSI-based Handover Method (RHM) approaches for the mobility scenario illustrated in Figure 1 with a TIME_TO_LIVE (*TTL*) tree times larger than the interception area of the APs; a) illustration of the node accessibility or inaccessibility using the two approaches; and b) the number of messages exchanged between the node and the APs.

Next, following the same above-described configuration scenario, the TTL was reduced until the mobile node turns always accessible during the travel using the RHM approach. To ensure the continuous connectivity to the node using RHM, the TTL (*TTLR*) was reduced to 1/4 of the previous experience. Figure 6 presents the corresponding results. In Figure 6 a), it can be seen that node is always accessible using the two approaches but Figure 6 b) shows that number of messages exchanged for the RHM approach increase drastically to 32 messages. At each *TTLR*, the node sent a RNEW message and receives the corresponding RNEWREG message. At this time, the node evaluates if the RSSI of the received message is under the RSSI threshold. At the *8*TTLR* time, the RSSI of the received message is under the threshold, then the node sends a ROUTE message retrieved by AP_2 and a BREAK message to AP_1, performing the handover for the mobile node. In this experience, the node is always accessible for the two methods. In terms of exchanged messages, it is shown that HHM approach (with 18 messages) is much better than the RHM approach (with 32 messages exchanged). Considering that messages exchanging is one of the most penalized operations for nodes' batteries it can be concluded that to guarantee a continuous connectivity to mobile nodes, the HHM mechanism performs better than the RHM approach.



a)

b)

Figure 6 – Performance evaluation of the proposed Historic-based Handover Method (HHM) and the RSSI-based Handover Method (RHM) methods for the mobility scenario illustrated in Figure 1 with a TIME_TO_LIVE for RHM (*TTLR*) four times smaller than TIME_TO_LIVE for HHM (*TTLH*); a) illustration of the node accessibility or inaccessibility using the two approaches; b) number of the exchanged messages between the node and the corresponding APs.

V. Conclusion and Future Work

New ICT based solutions for eHealth care are very promising approaches, however, to be efficient they should also be improved for being accepted by patients. This paper studied ubiquitous mobile solutions for body sensor networks on healthcare monitoring. BSN operating IPv6 over Low-power Personal Area Networks stack (6LoWPANs) were considered. Given the requirements of medical BSNs for healthcare and biofeedback, and to improve the patients' quality-of-life with mobility, it was demonstrated that patients monitoring with mobile ubiquitous support on hospitals is a key issue. A new ubiquitous mobility approach for BSNs, the proposed handover method (PHM), assuming continuous monitoring on hospitals was introduced and described. This method is based on a historic list of previous registered nodes on each AP, using caching mechanisms, and the initiative to contact previous registered body sensor nodes is centered on APs because they do not have energy consumption constrains. This approach emphasizes unicast communications instead of multicast. It was shown that proposed mobility mechanism performs better when compared with the RSSI-based handover method (RHM).

The evaluation of this promising approach was performed and validated by simulation encouraging the authors to enhance this method and evaluate it in real scenarios. The paper also offer important insights for furthers studies on ubiquitous healthcare using wireless sensors and other networked devices.

Acknowledgements

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Chapter 5

MAC Layer Handover Mechanism for Continuous Communication Support in Healthcare Mobile Wireless Sensor Networks

This chapter consists of the following article:

MAC Layer Handover Mechanism for Continuous Communication Support in Healthcare Mobile Wireless Sensor Networks

João M. L. P. Caldeira, Joel J. P. C. Rodrigues, and Pascal Lorenz

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MAC Layer Handover Mechanism for Continuous Communication Support in Healthcare Mobile Wireless Sensor Networks

João M. L. P. Caldeira • Joel J. P. C. Rodrigues • Pascal Lorenz

Abstract The use of wireless sensor networks (WSNs) is growing up in the last few years. Therefore, new challenges arise every day and one of the emerging challenges in WSNs is the nodes mobility support. This feature increases the application areas of these technologies but also raises new challenges to solve. This paper proposes a new handover mechanism, called Hand4MAC (Handover Mechanism for MAC Layer supporting Continuous Communication in Mobile Wireless Sensor Networks), to deal with body sensors mobility in scenarios where patients are hospitalized. This approach tries to provide continuous monitoring and communication with these sensor nodes when they move across different access points wireless coverage range. The proposed method for medium access control (MAC) layer considers that nodes remain within the same network. The evaluation study of the proposed algorithm was performed by simulation and evaluated in comparison with the well-known RSSI-based handover algorithm. It was concluded that Hand4MAC performs better and reveals promising results for real deployment.

Keywords Body Sensor Networks • Healthcare Applications • Mobile Health • Mobile Monitoring • e-Health • Handover • Mobility • Wireless Sensor Networks • MAC Layer

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1 Introduction

Wireless sensor networks (WSNs) have grown very fast in the past few years. Their applications in several areas (e.g., military, animal control, environment and biofeedback monitoring) promote the evolution of scientific research in these technologies [1]. However, due to the continuous evolution of these new technologies, several novel challenges and problems arise every day. WSNs are composed by several nodes able to collect sensorial data, deployed along a monitored field. These sensors collect data and send them to remote stations/repositories. This operation is supported by a network infrastructure that allows the transmission of (raw) data from the nodes to the remote entities for storing [2]. Sensor nodes, compliant with wireless technologies, are small devices usually powered by batteries and with low processing capacities [3]. In most of the applications it is not suitable to replace or even to recharge the nodes power sources (batteries). Therefore, if the energy fails in a given node, probably, it will take a long time to get it operating again or forever. This situation could lead to the degradation of the overall network performance. Thus, the lifetime of nodes is a major handicap in WSNs operation. To deal with this weakness, recent studies try to optimize operations in these networks [4]. It is inevitable to compare WSNs with the available and well-known Wi-Fi networks. Despite their similarities, most of the technologies applied in Wi-Fi are not suitable for WSNs due to their power hungry procedures. Therefore, new challenges were introduced in WSNs due to their limitations in terms of proceeding capabilities and manly on the energy constraints in the nodes [5].

The construction of WSNs can vary in their constitution, but usually, a WSN is a combination of several sensor nodes placed along a monitored area (forests, enemy fields, human bodies, etc.) [6, 7]. Access points (APs) that interface the access to/from the nodes from/to the remote stations/repositories (usually through the Internet) cover these nodes [8]. Although, in this traditional architecture several aspects are application dependents. One of these aspects is the nodes mobility. Most of the recent WSNs implementation use static nodes. This means that nodes placed in a monitored field remains in their positions all the time and it is not suitable for all the situations. In scenarios where the object/phenomenon/parameter to be monitored changes its position along the time it is important that sensor nodes could move jointly with the monitored parameter. In these scenarios, WSNs became mobility-enable since it is assumed that nodes could move freely around the monitored geographical area [9]. This feature introduces several new challenges and issues on WSNs [10-14]. The network coverage is one of these problems and, consequently, the access by nodes connected to the network infrastructure [15]. If a node moves around a monitored area covered by several APs this means that node must change its AP attachment along the trajectory in order to communicate with the network infrastructure [16]. The process of changing its point of attachment to the network is known as handover. In mobile WSNs scenarios, handover mechanisms support nodes mobility. Recently, several approaches were proposed to optimize the energy wasting with these mechanisms [17-22]. Despite all these proposals sounds promising, the authors consider that solutions are not yet satisfactory. Several possibilities are still unexplored regarding mobility support in

WSNs. Then, this paper focuses on handover mechanisms compliant with the standard IEEE 802.15.4 assuming mobility support in controlled scenarios. This handover mechanism was developed concerning the evolution of the handover procedure introduced in [23]. This work was developed regarding a hospital infirmary as a target scenario. The use of WSNs in this scenario supports the monitoring tasks of hospitalized patients [24]. Patients carry a batch of sensor nodes attached to their bodies. Each sensor node collects one or more bio physiological parameters, which are used to evaluate the overall health state of a given patient [25, 26]. To improve the quality-of-life of hospitalized patients it is important to offer them free walking around the perimeter of an infirmary. These walks should not disturb the monitoring process neither the patients' comfort. The sensors nodes used for patients monitoring are IEEE 802.15.4 compliant and powered by batteries. The standard IEEE 802.15.4 [27] considers two operation modes, beacon-enable and non-beacon. In beacon-enable operating mode it introduces the use of superframe structure to split time into different transmission periods. The standard refers to four time slots, namely, beacon period, contention access period (CAP), contention free period (CFP), and inactive period. The nodes use the inactive period to enter in sleep mode. This behavior does not guarantee that nodes are reachable all the time since they could lose its contact with the AP during this period without knowing it. In IEEE 802.15.4 non-beacon, it is used the carrier sense multiple access with collision avoidance (CSMA-CA). This transmission mode performs a clear channel assessment (CCA) before sending the radio channel. If the channel is not clear, the algorithm waits for a random time before trying to retransmit. When sending a message, this algorithm could ask for a reception acknowledgement or not (it is configurable) [28]. This IEEE 802.15.4 operation mode could guarantee a continuous communication to nodes in conjunction with a handover mechanism proposed in this paper, named Handover Mechanism for MAC Layer supporting Continuous Communication in Mobile Wireless Sensor Networks (Hand4MAC).

Assuming that nodes belong to the same network, the Hand4MAC algorithm was proposed over IEEE 802.15.4 non-beacon. However, in theory, this approach consumes more energy (due to the inexistence of nodes sleep periods) than a beacon-enable approach. Beacon-enable methodology allows nodes to be unreachable during the sleep periods. Moreover, when nodes are in sleep mode they could not communicate, meaning that APs have to cache the request to nodes during this period of time avoiding real-time communications.

This paper proposes a reliable and robust handover approach over IEEE 802.15.4 non-beacon mode. The proposed method was evaluated by simulation in comparison with the most used handover decision algorithms. The decision to set the best time to perform a handover operation is one of the main issues in these mechanisms. Two main approaches are used, one to establish a new link-after-break and another to establish a new link-before-break. The Hand4MAC algorithm must guarantee continuous nodes connectivity, so it was used the link-before-break approach.

The rest of this paper is organized as follows. Section 2 reviews the related literature on handover proposals applied to WSNs. Technical details of the proposed handover method are described in Section 3 while the network scenario is presented and described in Section 4. The performance evaluation of the Hand4MAC mechanism is presented in Section 5. Finally, Section 6 concludes the paper and point out further research directions.

2 Related Work

Mobility support is a recent research topic in WSNs. Most of the works proposed up to now in WSNs domain use static elements. Therefore, only few proposals were presented about mobility in WSNs. This paper focuses in handover mechanisms for mobility support in WSNs. Thus, this section reviews the most recent and relevant literature in handover mechanisms for mobile WSNs.

In [17], it was proposed a procedure for both inter and intra-mobility support of nodes in controlled WSNs. Since the focus of the contribution proposal is intra-mobility support authors only point out this procedure. The new intra-mobility support proposed in [17] follows a proxy-based approach. The APs (named proxy agents (PA)) measure the received signal strength indicator (RSSI) value of links. If the value of RSSI with a node falls below a threshold, the PA notifies another PA to start hearing for packets from this node. When a PA receives a packet from the node it informs the old PA by sending it the RSSI value of the received packet. The old PA verifies if the RSSI value is within a valid range and, if it is validated, the old PA informs the new PA that it could register the node. Finally, the old PA notifies the node about the new attachment point with the new PA. Analyzing this procedure it seems that to perform a handover operation a node must still accessible by the old PA to be informed by this one of the new attachment point.

A two phase handover procedure was presented by Fotouhi et al. [18]. This proposal uses two metrics to decide the need for a handover. These two metrics are the velocity of nodes (if available) and the RSSI value of links between nodes and APs. This proposal assumes that nodes send periodic probe messages to its current APs (associated APs) and receive, in return, acknowledge messages. In phase one, if the velocity of the node is unknown, the handover process is triggered when the received RSSI drops below a predefined threshold. Then, with the decision to proceed for a handover in phase one the procedure moves to the phase two. At this phase, the node sends periodic probe requests to all the neighbor APs (multicast) and waits for any probe acknowledge from APs. At this moment, the procedure enters in the decision phase of reassociation with a new AP. If several alternatives are available, the decision is based on a new metric - the link quality estimation (LQE). The handover procedure is then finalized by requesting reassociation with the chosen AP.

An approach to support WSN mobility in hospital facilities was proposed in [19]. This approach considers that all nodes have a base network and over the time they can travel to visited networks. When a node moves away from its base network coverage and its link quality drops beyond a predefined threshold it assumes that current router is no longer reachable. After that, the procedure is not clear in what happens, afterwards, for the node. It is not clear if the node starts to find a new router or if it waits until a new router finds it. Although, in this proposal, it seems that nodes allow periods of inaccessibility. When a node enters in a visited network it receives beacon packets from this network coordinator. Next, the node sends an association request with this network. After a successful association, negotiated between the base network and the visited network, data sent by the node to the visited network are forwarded to its base network.

All the above-described proposals use the link quality (RSSI) metric between the node and its current point of attachment as the main handover decision, comparing it with a predefined threshold. Continuous messages exchanges are performed for degradation monitoring of this value beyond the predefined threshold. Whether this threshold is crossed, it is time to find a new point of attachment. The Hand4MAC method suppresses the control over link quality value. Therefore, it does not need continuous messages exchanges to get this value.

Petäjäjärvi *et al*. [20] proposes a soft handover procedure for WSNs. This procedure works as follows: the APs (named gateways (GW)) periodically spread route advertisement (RA) messages to announce their presence. If a node receives a RA from a GW it checks if it has already register with it or not. If not, the node replies with a registration message. This approach allows nodes to be registered with multiple GWs. Each registered GW is stored into nodes' local memory. Currently, this approach does not perform a real handover operation. Nodes collect all the GWs that are in its range as registered GWs. Then, nodes manage the removal of the GWs that become inaccessible by evaluating the ration of expected RA messages received from each registered GW. Although, the authors of this paper consider this approach very promising and argue the use of multicast RA sent by the GWs (as proposed in ND methods [29]) continues to be a handicap. The proposed approach eliminates the need of this ND feature.

In [30], a mobility approach for WSN based on Sensor Mobility Proxies (SMPs) was proposed. These entities manage the link quality of all mobile nodes in their coverage range. This information is used to decide when a handover should be performed for a specific node. The procedure for handover is executed through a shared backbone that interconnects all the SMP available on the WSN. To keep the information of link quality, SMPs and nodes must exchange periodically probe messages. Next, the proposal of a new handover approach (Hand4MAC) for body sensors with mobility support is presented.

3 Proposed Handover Mechanism

When a sensor node moves across different AP wireless coverage range it should change its registration in order to remain accessible. Knowing the exact moment to change the registration it is one of the most challenging issues in handover procedures. Some of the proposals described in Section 2 use the approach register-after-break. This means these solutions allow inaccessibility periods. Thus, using this approach in continuous access solutions it is not suitable. It is assumed that nodes must be always reachable. Therefore, the proposed method uses the link-before-break approach.

In the proposal of Hand4MAC method the following assumptions were considered:

(1) The nodes are always within the same network, i.e., its Internet protocol (IP) address never changes;

(2) The nodes must be always reachable (all the time) along the infirmary;

(3) After a short period of time, nodes are well-known by the infrastructure and it is not common changing these nodes, i.e., the nodes remain the same for long periods of time (controlled environment).

Assuming that nodes are always within the same network, it is not necessary to support handover at layer 3 (L3) – open systems interconnection (OSI) model. Therefore, the proposed handover method works over OSI model L2 (MAC layer). Ongoing projects use neighbor discovery (ND) algorithms over L3 to support mobility in WSNs [31]. The current version of "ND optimization for low power and lossy networks (6LoWPAN)" draft (version 18) [29] address some issues related with mobility on WSNs, but it does not deal very well with uninterrupted access to nodes, which is the second assumption.

Fig. 1 and 2 present the flowcharts of nodes and APs firmware operations to support the Hand4MAC algorithm. For an easy comprehension of the terminology used in the flowchart representation, it is the same that can be found in the description below.

When a node is new for the network it starts to find an AP for registering. This task is accomplished by sending periodically (at time-to-live – TTL – interval) multicast *route advertisement* (RA) messages. If an AP receives a RA from a node it creates a new entry in its local *cache table* (CT) storing the node's address. This table is used by APs to search for all the available nodes there. This search is performed by sending unicast *find* messages to each node at very short intervals (~ 1 second – an explanation for this value could be found at the end of this section). If a node receives a *find* message it means that it is within the coverage range of an AP that is not registered there. At this point the node sends an *lqi-probe* message to the current AP and, in turn, it receives from this an *lqi-probe-acknowledge* message. If this probe fails the process suppress the next comparison and proceed directly to the association of this new AP. This probe is used to update the value of the link quality indicator (LQI) for the current AP. Then, the node verifies if the LQI of a new AP is better than the current one. If so it sends a unicast *find-acknowledge* message to the new AP to perform the new association and sends a unicast *break* message to the current AP to notify it about the disassociation. After receiving a *break* message the current AP moves the node entry from the *registered table* (RT) to the CT. After receiving the *find-acknowledge* message, the new AP instructs the GW to insert a new entry in *access table* (AT) with the new register. This new entry is inserted at the top of the table in order to know that newest registrations appear at first in a search for that node. This action avoids that oldest AP also needs to notify the GW about the disassociation. Removing old repeated entries of nodes it is part of the GW AT maintenance tasks.

The *registration table* (RT) is used to store the information of the registered nodes. This table creates a new entry whenever the AP receives a *find-acknowledge* message. At this time the node is removed from CT and inserted in RT. It is also associated a *timestamp* to the registration action for this node. At TTL periods of time expiration the nodes should renew their registration with already registered APs by sending a unicast *renew-register* message, which returns a *renew-register-acknowledge* message. If the renewal is not performed the AP moves the node from RT to CT.

When all the nodes become known by all the APs, the handover process is guarantee by the unicast *find* messages sent from the APs to the unregistered nodes that enter in their coverage range. This method avoids that nodes and APs must exchange regularly messages only to verify that they remain accessible to each other.

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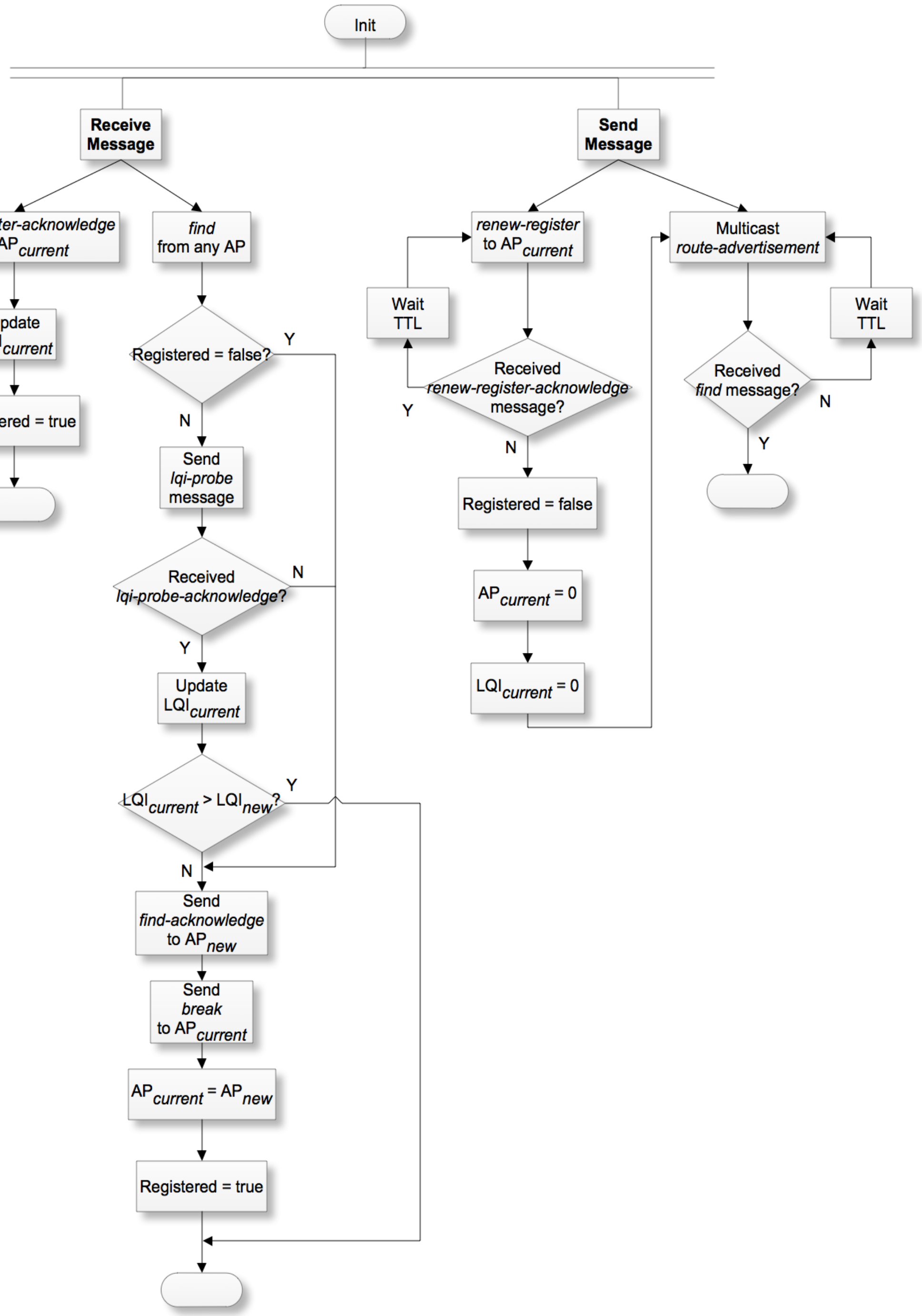

Fig. 1 Hand4MAC algorithm – nodes perspective

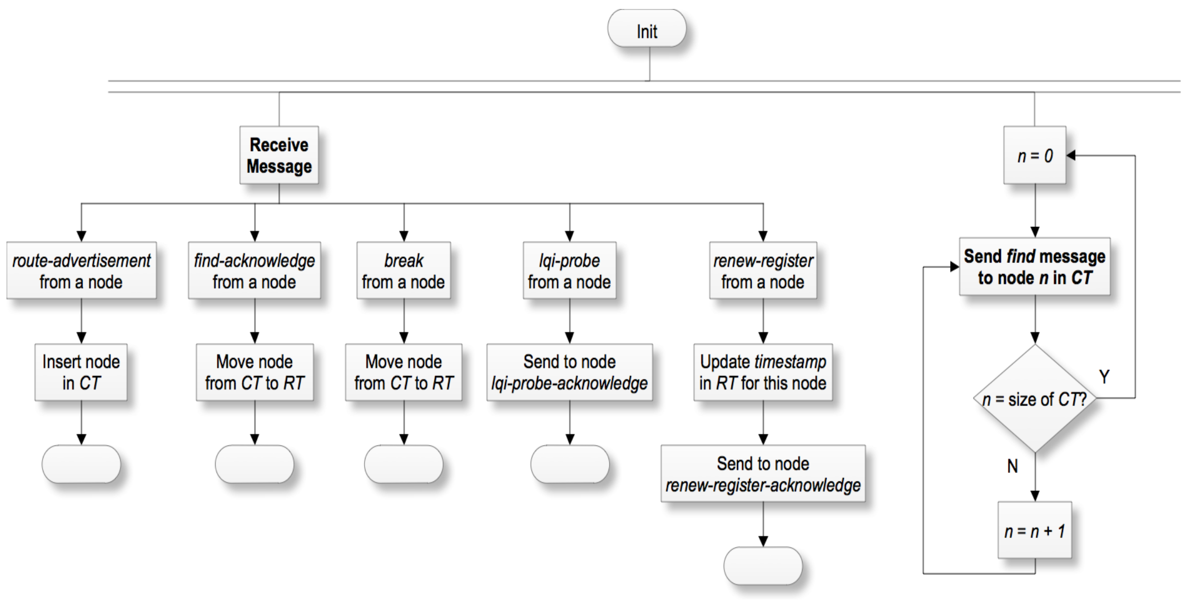

Fig. 2 Hand4MAC algorithm – access point perspective

3.1 Assumptions on *find* messages

The coverage range of each AP is approximately ten meters, which means that 20% of this value corresponds to 2 meters. When designing the scenario it was tried to overlap the coverage range of the adjacent APs about 20% to guarantee continuous access to the nodes. Considering that average speed of a human walking is about 2 meters per second (m/s) this means he/she takes about 2 seconds to travel the previously mentioned 2 meters. Using a time interval of 1 second between *find* messages in the AP firmware it seems a good choice to guarantee that a node that enters in a non-associated AP's coverage range (overlapped in 20% with its associated AP's coverage range) receives a *find* message from this one before losing connection to its associated AP. This way, the handover operation could be performed in a link-before-break manner.

4 Network Scenario

Monitoring hospitalized people to control their overall health conditions is needed. Depending on diseases, patients need a careful and continuous monitoring control for specific human parameters (e.g., peripheral/core body temperature, pulsation, movement, electroencephalography (EEG), electrocardiography (ECG), …). The process of data collection and turning them available may be performed by a WSN infrastructure. In this paper, the performance of the proposed handover solution is evaluated in an infirmary scenario. The used WSN comprises several body sensor nodes. These nodes are able to collect body parameters and send them wirelessly through APs geographically distributed along the infirmary. These APs are responsible to get network access to all the nodes within their coverage range. The APs distribution assures the coverage of an infirmary. In order to guarantee a continuous communication with nodes, the coverage range of each AP was overlapped by about 20% with the adjacent ones. Fig. 3 depicts an illustration of a hospital infirmary that was used as a scenario for this proposal evaluation. This infirmary comprises nine rooms, a physician room, a treatment room, a nurse room, a reception, a medication room, a storage area, and a sitting and dining room. To cover all this area fourteen APs with a coverage range of about ten meters were used. As may be seen in Fig. 3, the APs distribution guarantees that coverage ranges of adjacent APs are overlapped about 20%.

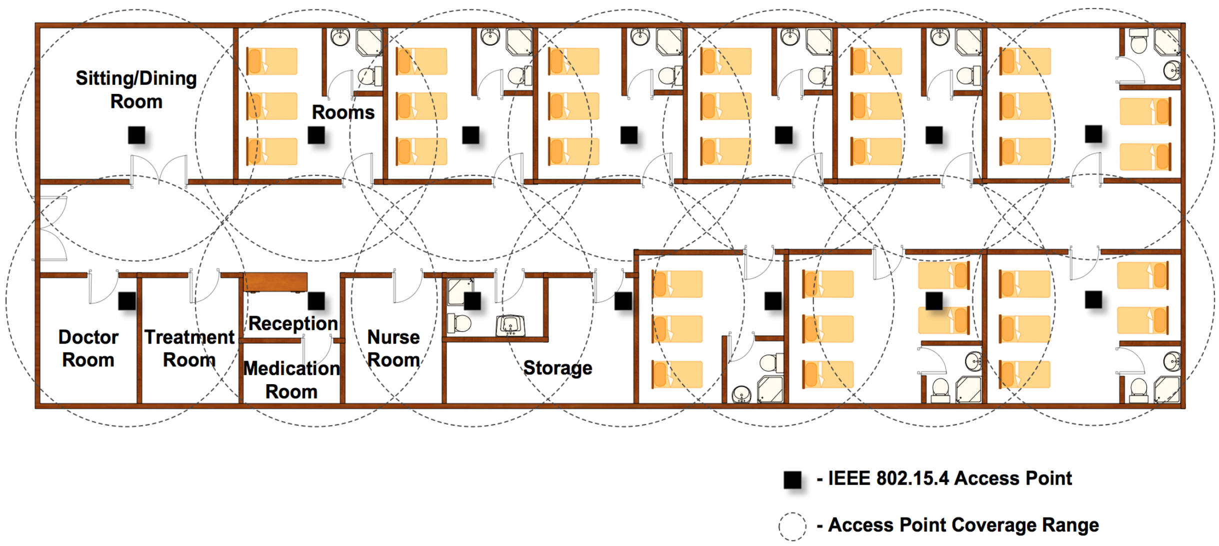

Fig. 3 Illustration of a hospital infirmary covered by access points with IEEE 802.15.4 support

Each patient moves freely around the infirmary carrying a batch of small sensor nodes for biofeedback real-time monitoring. These small nodes are powered by batteries and incorporate a CC2420 radio module [32] with IEEE 802.15.4 support [33]. The APs, also compliant with the standard IEEE 802.15.4, are powered by electricity. A single gateway (GW) acts as an interface between the APs and the Internet through the hospital network. Fig. 4 presents detailed network architecture of the BSN used in the above-described scenario. The GW maintains a table (*Access Table*) that matches each node to the AP where it is registered. This table is used for routing remote requests to a specific node. In this way, the GW sends this request to the corresponding AP. This table is updated by AP requests whenever a change is performed on its local tables. Each AP uses two local tables (*Registration Table* and *Cache Table*) to manage nodes registration on it. In Section 3, it was detailed the operation of these tables.

It is assumed that both APs and nodes used for the performance evaluation study of this proposal have about ten meters of coverage range. There are commercial solutions of IEEE 802.15.4 APs with larger coverage ranges, but they are not suitable for this scenario given the need of bidirectional communications. When a patient walks in the infirmary, he/she travels along several coverage ranges by different APs. This situation implies that sensor nodes carried by patients should perform handover between APs for continuous network connectivity.

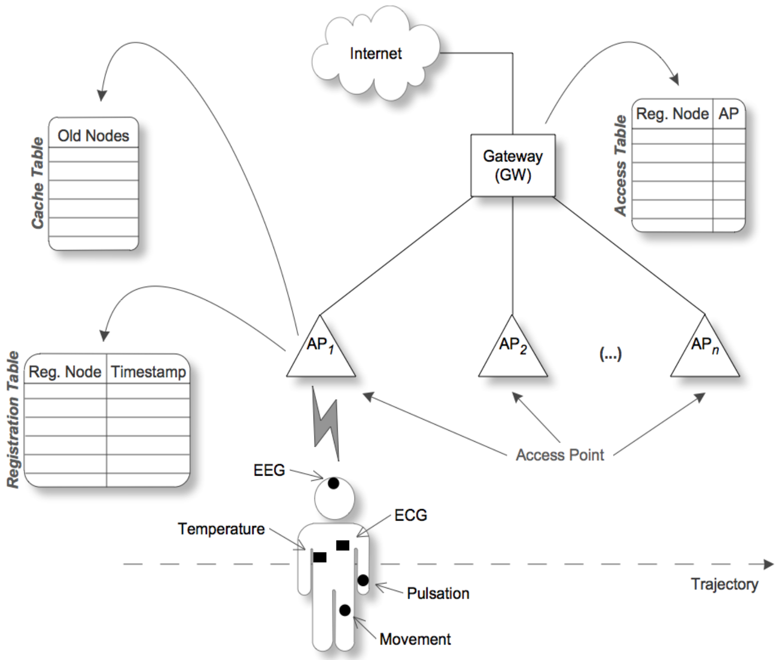

Fig. 4 Illustration of the sensor network architecture

5 Performance Evaluation

This section focuses on the performance assessment of the proposed handover mechanism (Hand4MAC) in comparison with RSSI-based handover algorithm [17-19]. This study was performed by simulation using the OMNeT++ [34]. The proposed protocol was developed over IEEE 802.15.4 implementation from MiXiM package [35]. MiXiM is a simulator of wireless and mobile networks for OMNeT++. In this work, the implementation of CSMA-CA transmission mode with non-beacon from the standard IEEE 802.15.4 available in MiXiM package was used. As above described, the proposed protocol was developed at MAC layer. At this layer, a new module to control and process all the messages involved in handover operations was included. The network settings considered in the scenario described at Section 4 and the results analysis are presented in the next sub-sections.

5.1 Network Settings

To evaluate the performance of the Hand4MAC algorithm the network scenario presented in Fig. 3 was used. This scenario was reproduced by the simulation tool, as may be found in Fig. 5. The scenario was created inside an area of 46,0 by 14,5 meters. This area represents the infirmary space. Along this area fourteen static APs were placed. In the simulation scenario, each AP was disposed according to the distribution depicted in the above-described real scenario. These APs run the firmware algorithm described in Section 3 (illustrated in Fig. 2). This algorithm was deployed in the MiXiM IEEE 802.15.4 standard implementation.

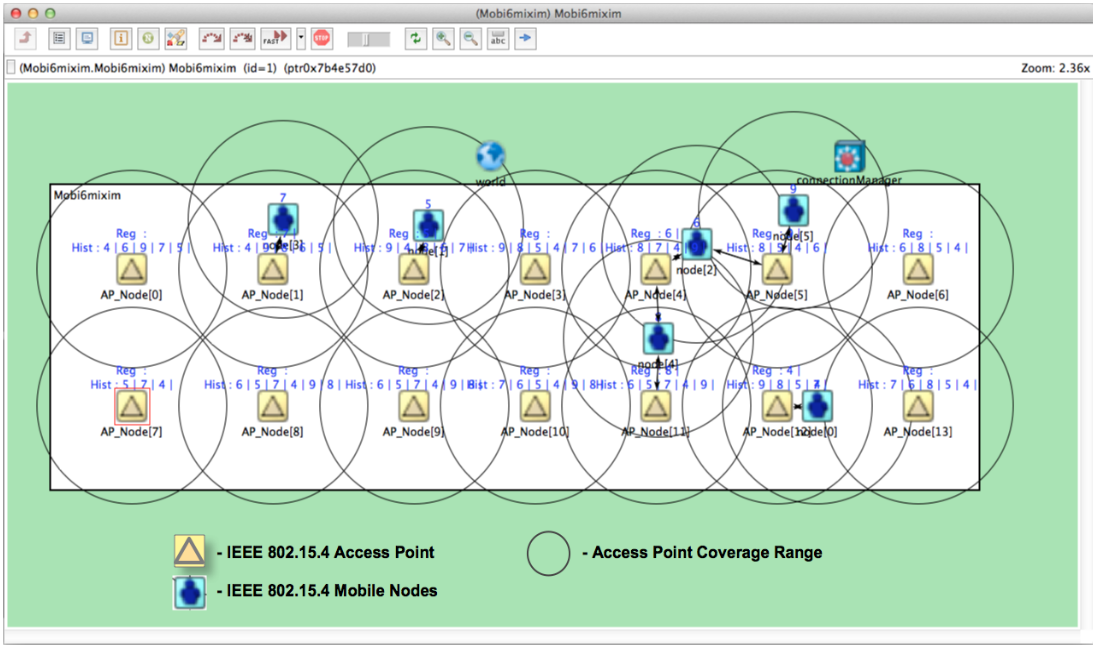

Fig. 5 Simulation scenario regarding a representation of a hospital infirmary area, with the location of access points (squares with a triangle) and the mobile nodes (squares with a human silhouette)

Six mobile nodes placed in random positions along the scenario area were considered (Fig. 5). In the figure, mobile nodes are represented by a square with a human silhouette. These nodes move randomly with a constant speed of 2m/s to simulate patients walking around the infirmary area. These nodes follow the Hand4MAC algorithm presented in Section 3 (Fig. 1). The algorithm was developed for the MiXiM IEEE 802.15.4.

The standard IEEE 802.15.4 implementation used in the study follows the proposal presented in [36] with the same settings. All the nodes are equipped with a CC2420 radio transceiver [32] and the simulation parameters used for the operation of this module also are presented in [36].

As above-mentioned, a network performance comparison study between the Hand4MAC algorithm and the handover method used in [17-19] was realized. From now on, to get an easier reference of the method proposed in those works will be referred to as RSSI threshold-based method (RTHM). This study considers two cases for the described scenario.

In the first case study, the simulation parameters were the same for the two methods and are listed on Table 1. The nodes move randomly with a velocity of 2m/s. It was used a time-to-live (TTL) value equal to 5 simulation time units (measured in seconds). This value defines the time intervals among probe messages exchanged between nodes and associated APs. In RTHM, following the algorithm proposed in [18] (phase one), the node receives the probe acknowledge message and compares the RSSI value with the predefined threshold. After this comparison, the algorithm decides if a handover is needed (RSSI < threshold) or not. The simulation time for each experiment was 1000 simulation time units.

Table 1 Case Study 1: network parameters

Parameter	Value
Velocity	2 m/s
Time-to-Live (TTL)	5*
Simulation Time	1000*

* Measured in simulation time units (seconds)

For the second case, the simulation parameters were only changed for the RTHM, as may be seen in Table 2. The velocity of the nodes and the movement behavior remains the same as the previous case study. Regarding the TTL value, for the RTHM, 1 time unit was considered. For the Hand4MAC approach, this value remained the same as considered in previous case study (5 time units).

To get representative and meaningful results the batch means method was followed [37]. A set of 30 experiments was performed for each result using different seeds for random calculations. The results under analysis in next sub-section represent the average values of 30 experiments.

Table 2 Case Study 2: network parameters

Parameter	Value	
	RTHM	Hand4MAC
Velocity	2 m/s	2 m/s
Time-to-Live (TTL)	1*	5*
Simulation Time	1000*	1000*

* Measured in simulation time units (seconds)

5.2 Results Analysis

The performance analysis of the two methods under comparison was performed in two different ways. First, the signaling costs for each method was evaluated in three performance metrics, considering the number of received messages, sent messages, and sent multicast messages. This study was performed for all the 6 mobile nodes considered in the network scenario. Then, the connection status between each node and the network backbone was evaluated, i.e., for each node, it was continuously tested if it was remained reachable by the registered AP or not. In other words, if a node could not contact with its registered AP, then it was not connected to the network backbone (so, it was unreachable). The analysis of this metric allows the performance evaluation of the network in terms of the continuous access to nodes.

Case Study 1

For this first case study, the results of signaling costs obtained for both considered methods are presented in Fig. 6. As may be seen in the figure, it can be concluded that, although the number of received messages were, in average, almost the same for the both mechanisms, the Hand4MAC sent less messages and used significantly less multicast messages. The average number of received messages for RTHM was about 349 and 350 for Hand4MAC. In terms of sent messages, RTHM used an average of 366 messages and 258 for the present proposal. Regarding multicast messages, RTHM sent 184 messages, in average, while Hand4MAC algorithm only sent 10.

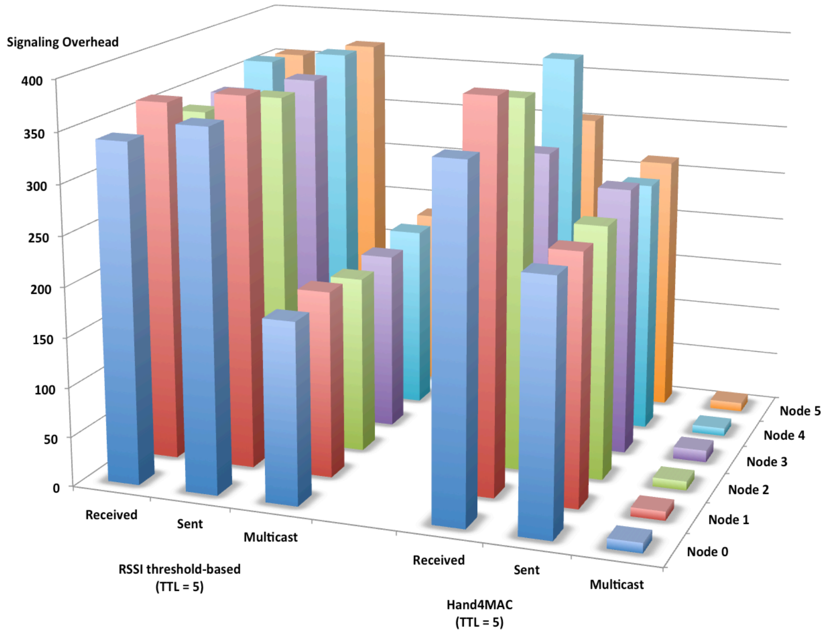

Fig. 6 Signaling overhead of RSSI threshold-based and Hand4MAC mechanisms in function of the number of sent messages, received messages, and sent multicast messages with TTL=5 and 6 mobile nodes

As an example of nodes connection status during experiments, Fig. 7 and 8 depict the connectivity to node 4 using the two handover methods. This result was obtained during the 16th experiment (out of 30). Fig. 7 presents the connection status of node 4 using RTHM. Considering that "*1*" means connected to an AP (reachable) and "*0*" not connected (unreachable), it can be seen that using RTHM, the node is unreachable during a longer period of time while Hand4MAC shows better results (Fig. 8). The period of time that each node remains reachable is presented in Table 3 (measured in time percentage). On average, when Hand4MAC algorithm is used, the nodes remained reachable about 98% of the time while, for RTHM, this value was only about 87%. Analyzing these results it can be concluded that Hand4MAC could almost guarantee a continuous connectivity to nodes unlike the RTHM.

As may be seen in Fig. 8, there are several periods of time where the node is unreachable. It occurs when a node arrives at first time to the coverage range of a given AP and never was registered on it. In upcoming times that node arrives at this AP coverage range it will receive the *find* message. For RTHM, the unreachable periods of time occurs when a node moves out of a registered AP coverage range. At this time it takes TTL to get a probe message and to compare the RSSI value with the threshold. This means that node only perceives that is out of range just after TTL expires. Then, it starts to look for a new AP.

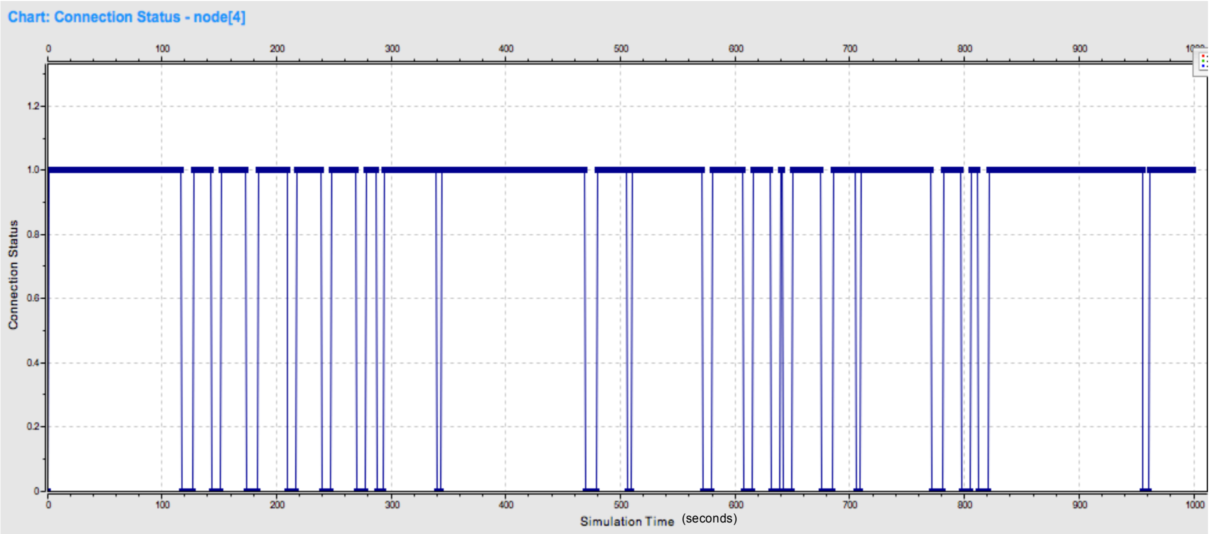

Fig. 7 Connection status of node 4 for RSSI-Threshold Handover Method with TTL=5

("1" - reachable; "0" - unreachable)

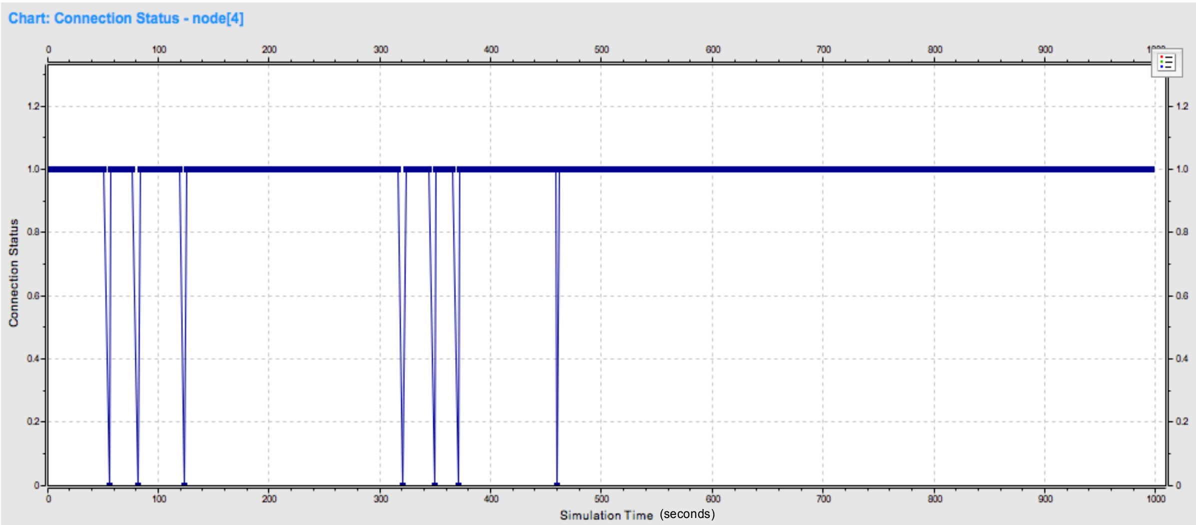

Fig. 8 Connection status of node 4 for Hand4MAC with TTL=5

("1" - reachable; "0" - unreachable)

Table 3 Percentage of time that each node remains reachable when using the two methods (TTL=5)

Node	RTHM	Hand4MAC
Node 0	87.73584%	97.94988%
Node 1	88.56839%	98.12889%
Node 2	84.08018%	98.02197%
Node 3	87.26415%	97.73195%
Node 4	88.16037%	98.49785%
Node 5	86.51179%	98.37398%
Average	87.05345%	98,11742%

Case Study 2

For this second case study, the TTL value used in the RTHM was reduced to 1 time unit. All the other parameters remain the same considered in the case study 1 (Table 2). This change aims to reduce the time interval to exchange probe messages between mobile nodes and their registered APs. This means that nodes perceive earlier they lost contact with their registered APs. As result, it was expected this change increasing the time each node remained reachable by the network. Furthermore, the connectivity to nodes was increased from about 87% to almost 98%. This behavior can be observed in Fig. 10 and Table 4. This figure presents the connection status of node 4 during the 16th experiment (out of 30). Although this improvement, the signaling costs increased significantly for all the performance metrics under evaluation, as may be seen in Fig. 9. Particularly, the number of received messages was about 1873 messages, representing an increase of about 536% when compared to the previous case study. Regarding the number of sent messages, RTHM obtains a result of 1896 messages on average. This behavior represents about 518% more messages sent than case study 1. The number of multicast messages increased also from 184 to 950 messages. This reflects an increase of about 516%.

Considering the TTL change from 5 to 1 time unit and comparing the Hand4MAC approach with the RTHM, it is observed that connectivity to nodes is now almost the same (about 98% for both mechanism). In terms of signaling costs all the performance metrics considered in the study increased significantly on RTHM, as may be seen if Fig. 9. The difference among received messages between RTHM (1873 messages) and Hand4MAC (350 messages) was about 535%. RTHM sent 1896 messages while Hand4MAC only sent 258 messages. The difference was about 735% on average. Regarding multicast messages, the difference is about 184 to 10 messages for Hand4MAC showing about 1840% more messages for RTHM.

Concluding, for RTHM, when TTL is reduced, the period of time that nodes are reachable increases. However, the number of exchanged messages (sent, received, and sent multicast messages) increases significantly. As a result, the lifetime of nodes batteries will be strongly reduced. Sending and receiving messages represent one of the most energy consumption tasks. Furthermore, the results show that Hand4MAC method can almost guarantee continuous connection to the nodes (about 98% of the time) with reduced signaling costs. Then, it can be concluded that Hand4MAC mechanism presents better performance than RTHM and can be seen as a promised approach for MAC layer handover for continuous communication support in healthcare mobile WSNs.

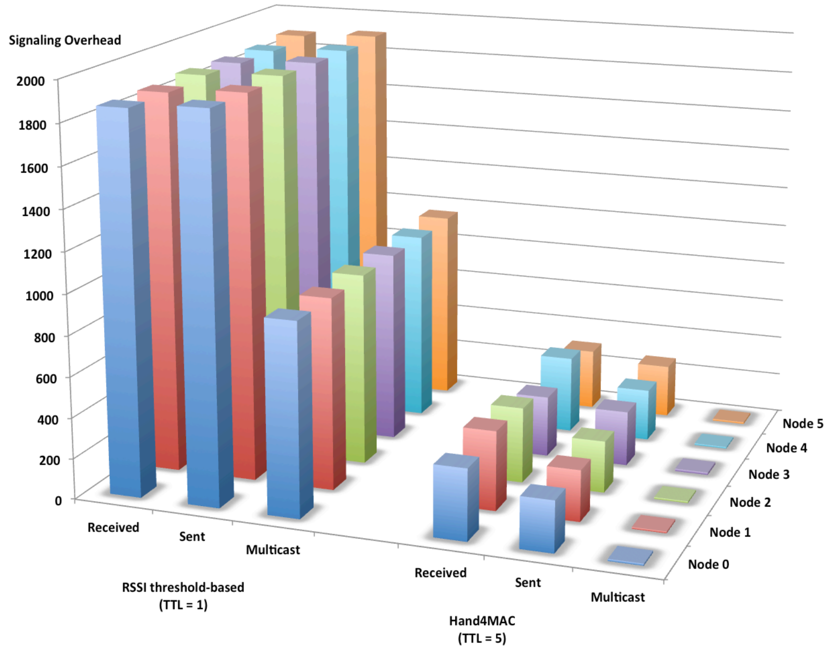

Fig. 9 Signaling overhead of RSSI threshold-based algorithm with TTL=1 and Hand4MAC mechanisms with TTL=5 in function of the number of sent messages, received messages, and sent multicast messages for 6 mobile nodes

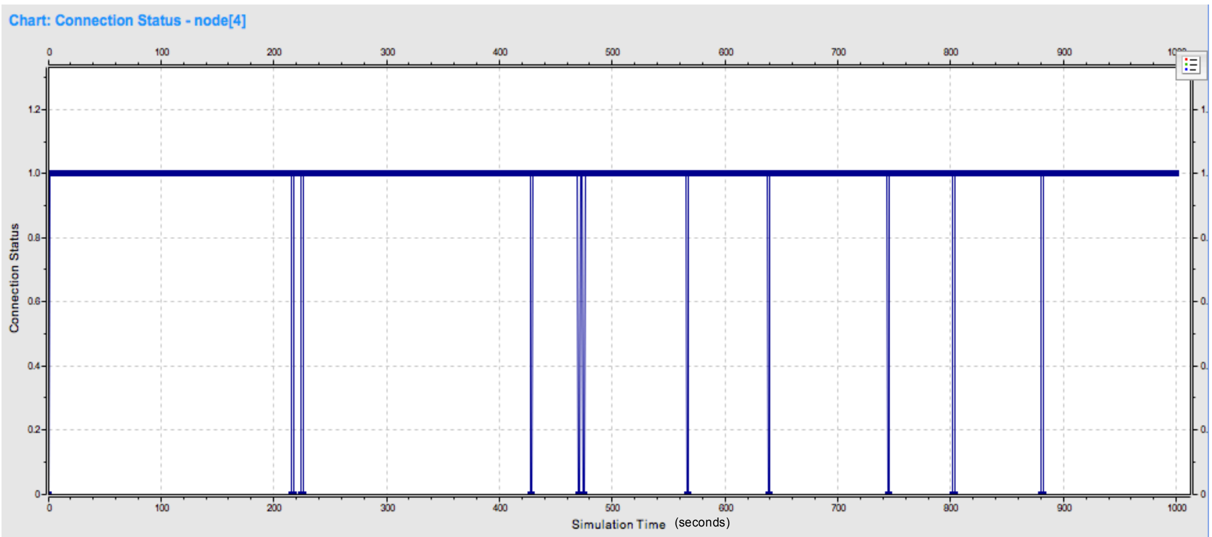

Fig. 10 Connection status of node 4 for RSSI-Threshold Handover Method with TTL=1

("1" - reachable; "0" - unreachable)

Table 4 Percentage of time that each node remains reachable when using the RTHM with TTL=1

Node	RTHM
Node 0	97.68950%
Node 1	98.70287%
Node 2	96.10822%
Node 3	97.89217%
Node 4	98.50020%
Node 5	97.51357%
Average	97.73442%

6 Conclusion and Future Work

This paper addressed the problem of MAC Layer mobility support in wireless and body sensor networks. This feature provides remote access to nodes moving across several access points' coverage range. In healthcare scenarios like hospital infirmaries it is possible to provide remote access (over a network backbone) to body sensor nodes carried by patients when they move around an infirmary. These nodes collect physiological parameters to monitor their health condition and send this data to remote repositories.

A new handover approach to support continuous communication to nodes in a mobile WSN was proposed. This mechanism, called Handover Mechanism for MAC Layer supporting Continuous Communication in Mobile Wireless Sensor Networks (Hand4MAC), offers overall best performance in comparison with RSSI threshold-based handover method (RTHM). The following performance metrics were considered: number of received messages, sent messages, and sent multicast messages. It was shown that Hand4MAC mechanism is a good solution for continuous connectivity to nodes traveling around an area covered by APs. This method uses a cache table in APs containing all previously registered nodes. Periodically, APs try to contact these nodes. If a node receives a contact from a previously registered AP it decides if it is helpful or not to re-register on this AP. This proposal was evaluated by simulation using OMNeT++. The results demonstrate that Hand4MAC method could almost ensure a continuous communication to nodes (about 98% of the time) with a reduced signaling cost.

Performance evaluation and real deployment of this proposal in a real test-bed should be part of further research works. The optimization of Hand4MAC mechanism also should be considered for future works.

Acknowledgments

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Chapter 6

Impact of Sensor Nodes Scaling and Velocity on Handover Mechanisms for Healthcare Wireless Sensor Networks with Mobility Support

This chapter consists of the following article:

Impact of Sensor Nodes Scaling and Velocity on Handover Mechanisms for Healthcare Wireless Sensor Networks with Mobility Support

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Abstract Health promotion in hospital environments can be improved using the most recent information and communication technologies. With small body sensor nodes it is possible to collect and monitor patients' bio-signals. Connecting these sensor nodes to the Internet enables remote access to collected data. Consequently, it allows for continuous and real-time monitoring and control of the patients' overall health conditions. In healthcare wireless sensor networks mobility support is a key issue to keeping patients under real-time monitoring even when they move around. To cover an entire infirmary with network connectivity, several access points should be considered. So, to keep sensor nodes connected to the network, they should change their access points of attachment when patients move to a new coverage area. This process, called handover, is responsible for the continuous network connectivity to the sensor nodes. This paper presents a detailed performance assessment study and analysis considering three handover mechanisms for healthcare scenarios (Hand4MAC, RSSI-based, and backbone-based). The study was performed by simulation using different numbers of sensor nodes and different moving velocities of sensor nodes. The results demonstrate that Hand4MAC solution proves to be the best solution to guarantee almost continuous connectivity to sensor nodes with less energy consumption.

Keywords Body Sensor Networks, Healthcare Applications, Mobile Health, Mobile Monitoring, e-Health, Handover, Mobility

1. Introduction

Wireless sensor networks (WSNs) are today a growing area in network domain applications. Following the vision of Internet of Things (IoT) paradigm WSNs becomes one of the most promising technologies able to potentiate that vision. Recently special focus has been devoted to WSNs application in healthcare facilities [1]. This new application emerged at the top of WSNs' research topics [2, 3]. The use of WSNs in healthcare domains tries to optimize operations related to patients' monitoring tasks. Traditionally, medical staff near patients perform these tasks at regular intervals. These traditional methods do not allow continuous control of certain health parameters. Moreover, if abnormal situations occur between these intervals, then the time needed to detect these could be too long. WSNs applied in healthcare scenarios (known as healthcare WSNs – HWSNs) can help medical staff to perform effective continuous and real-time monitoring of patients over all health conditions [4]. HWSNs can ensure a tight control of the patients' health parameters [5]. The monitoring tasks of patients' health parameters can be autonomous and automated using small sensor nodes attached to their bodies. Besides, these sensor nodes can be wireless, connected to a network infrastructure and so make them accessible anywhere, at any time over the Internet [6]. To promote the patients' comfort, the sensor nodes have to be tiny and light. These features limit the resources available in these devices. A sensor node is comprised of four main modules, namely, processing module, sensing module, communication module, and power module [7]. The processing module includes the microcontroller which is responsible for executing the software algorithms that operate the device; the sensing module which provides the sensor node with the ability to collect certain parameters; the communication module that allows the sensor node to send data wirelessly to a network typically compliant with IEEE 802.15.4 standard; the power module includes the power source (typically batteries) that keeps the sensor node alive [7]. Due to the sensor nodes' constraints, especially available energy, the operations performed by these devices should be optimized and the energy used in these operations minimized.

Using this technology in scenarios where the sensor nodes tend to be mobile, like healthcare scenarios, has brought new challenges to the WSNs research area [8-10]. Due to the limitations of the wireless signal propagation in situations like these [11], the creation of wireless networks for indoor environments should have several network access points (APs). Thus to cover the entire area of an infirmary, for example, several APs should be used. One of the main challenges in these scenarios is how to keep sensor nodes accessible to the network if they travel between several and different APs' coverage areas. To maintain sensor nodes accessible at all times these should not lose their connection to the network [12]. This means that the sensor nodes should be aware of the right moment to change their network attachment between two APs. This change should be performed within the overlapped coverage areas of two APs by evaluating the best solution to keep the sensor nodes connected to the network. This process of evaluating and changing the network point of attachment is called handover [13]. In deciding if it is better to perform a handover or not, the sensor node should be aware of certain network parameters. For handover decisions one of the most common parameters is the received signal strength indicator (RSSI). After receiving a message the RSSI value for that message can be obtained. Analyzing this value can estimate if handover is needed or not. Variations in RSSI values are related to the distance between the sender and the receiver. So, if the RSSI value becomes too small, it means that the sensor node is too far from the sender. This process is widely used to decide on performing handovers of sensor nodes in WSNs. Several approaches were recently proposed to estimate the best moment to perform handover of sensor nodes [14-17].

As explained, it is important to keep the patients' bio-parameters constantly under control. Thus, all the handover approaches should attempt to maximize the connectivity of sensor nodes to the network. In this quest, one of the main concerns is to reduce the energy consumption used in handover processes and thus increase the battery life of sensor nodes [18].

This paper presents a comprehensive study of the most significant proposals for handover in WSNs. It demonstrates, by simulation, the application of these proposals in a HWSN scenario. Several situations were evaluated and the results for each proposal were compared and analyzed.

The main contributions of this paper are the following:

- Presentation of a new handover mechanism called Hand4MAC;
- Performance assessment of the most significant handover mechanisms in comparison with Hand4MAC, considering healthcare scenarios;
- Analyzes of the influence of increasing the number of sensor nodes in a given scenario and their velocity in the connectivity with the network and in the energy expenditures.

The rest of the paper is organized as follows. Section 2 presents the most significant handover approaches presented in the literature. Section 3 describes the network model under study while section 4 discusses the performance assessment of the handover approaches used for this study. Finally, section 5 concludes the paper by pointing out the main conclusions of the study.

2. Handover Mechanisms for Intra-Mobility Support

This section provides an overview of the most recent WSNs handover mechanisms available for mobility scenarios. These solutions allow for communication to the sensor nodes even when travelling across several APs' coverage areas. This study devotes special attention to the application of these solutions in HWSNs scenarios [19]. Based on a comprehensive review of handover approaches it was concluded that they could be clustered into two groups. These two groups are referred to in this study as RSSI-based group and Backbone-based group. Next, a detailed description of each group is presented.

The RSSI-based group combines solutions based on continuous monitoring of RSSI values. The comparison of these values with a predefined threshold is used to decide if to perform or not a handover. In these solutions the sensor nodes and the associated APs exchange messages at short intervals. These messages are used to evaluate the RSSI value with the threshold. If the RSSI value received is below the threshold then the sensor node proceeds to handover and starts searching for a new AP to associate. Some of the proposed solutions that fall into this approach are [17], [16], and [20].

The backbone-based group combines solutions that use a shared backbone to interconnect all the APs. This backbone is used to exchange information between adjacent APs to guarantee the communication to sensor nodes. The handover process in these solutions is performed through the backbone by predicting the next AP in the route of the sensor node. In this approach each sensor node has a take care AP. This AP is responsible for the handover management of all the sensor nodes that it cares for. The choice of the take care AP for a certain sensor node based on the one with the best RSSI value. The link quality between sensor nodes and their take care APs are always under monitorization using short interval exchange messages. If deterioration on the RSSI value is detected then the take care AP informs the adjacent APs to start searching for this sensor node. This communication is performed using the backbone. When a new AP detects the sensor node this AP becomes the take care AP for that sensor node. This new AP then informs the previous take care AP of this and the handover is completed. The following solutions are examples of this approach [14], [21], and [22].

A new proposal for handover support in HWSNs is called Hand4MAC [23]. This proposal tries to minimize the continuous exchange messages used in the approaches described above to monitor the RSSI value. Nevertheless, this proposal also tries to guarantee continuous communication to the sensor nodes. The continuous exchange of messages contributes to the battery drainage and, therefore, to the reduced lifetime of sensor nodes. HWSNs can be considered controlled environments, i.e., after a short period of time, sensor nodes are well known for the infrastructure and it is uncommon to change these sensors (the sensor nodes remain the same for long periods of time). As such, this characteristic can be used to promote the mobility of sensor nodes. The idea is to consider that the APs can search for a specific sensor node instead of continuously monitoring the RSSI between the sensor node and the corresponding AP. If an AP finds a specific sensor node and the sensor node chooses to handover, then, the AP stops looking for it. If the sensor node moves into an overlapped coverage area of another AP, it starts to receive finding notifications from this new AP. At this time, the sensor node can decide to perform a handover or not. The decision can be based on the evaluation of the RSSI value. If the new AP has a better value of RSSI than the current one, then, the handover is performed. If not, the sensor node stays with the current AP.

3. Network Model

To evaluate the performance of the handover mechanisms in HWSNs, a network scenario that emulates a hospital infirmary was used. The infirmary area was considered as being 112,0 by 32,0 meters. It was assumed that each AP could cover (with wireless connectivity) an area of 10 meters radius. The definition of this value was based on the technical characteristics of Shimmer platform used for medical applications [24]. The sensor nodes also have a 10 meters radius coverage area to ensure bidirectional communication with the APs. To optimize the network connectivity the coverage area of adjacent APs was overlapped by 4 meters. Assuming these considerations to cover the overall area of the scenario, 14 APs were used. The network construction was based on IEEE 802.15.4 protocol. This protocol is one of the most commonly used for WSNs implementations. Thus, APs and sensor nodes were compliant with IEEE 802.15.4 communications. The movement of the sensor nodes follows a random strategy to simulate the patients moving around the infirmary.

Next, the simulation scenario construction to evaluate the performance of the above described handover approaches is detailed.

3.1. Network Settings

This study was performed through simulation using the OMNeT++ simulation tool [25]. To support the sensor nodes' mobility and IEEE 802.15.4 communications, the MiXiM package was used [26]. This package is a wireless and mobile networks simulator for OMNeT++. This study follows the settings presented in [27] for the IEEE 802.15.4 standard implementation. For simulation purposes it was considered that all the communication elements in the scenario were equipped with a CC2420 radio transceiver [28]. The simulation parameters used for CC2420 operation can be found in [27]. The design of the simulation scenario used for this study is presented in Fig. 1. This scenario reflects the representation of a hospital infirmary depicted in Fig. 2.

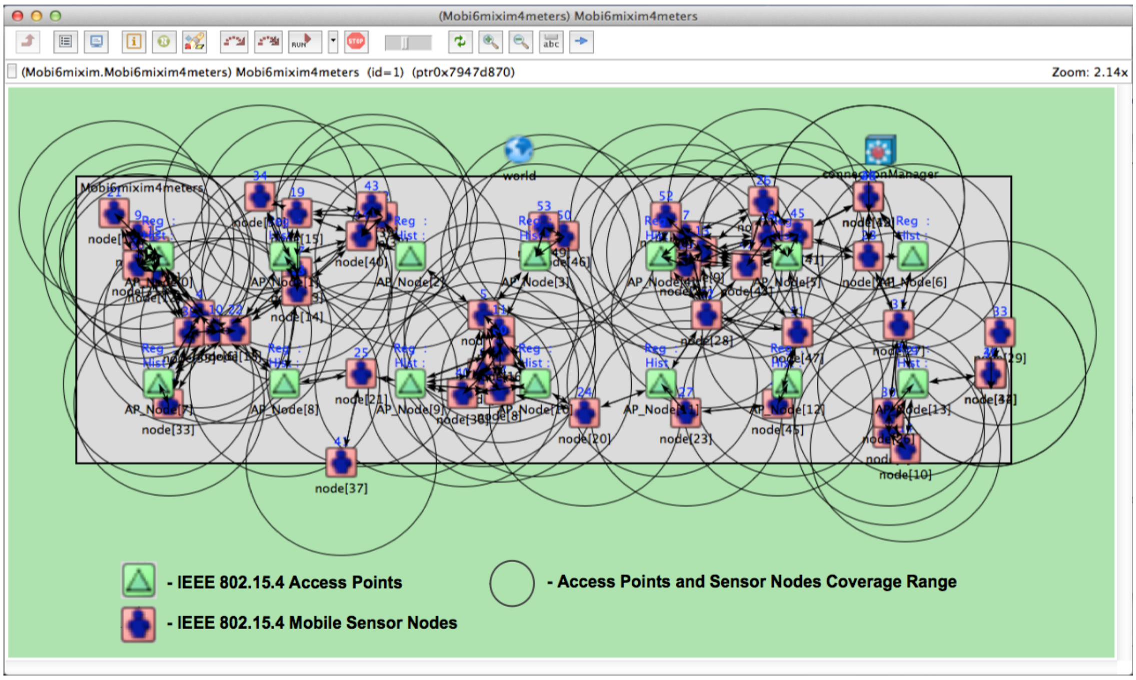

Fig. 1. Illustration of simulation scenario used in OMNeT++ representing a hospital infirmary. The access points' location is represented by a square with a triangle and the sensor nodes carried by the patients are represented by a square with a human silhouette

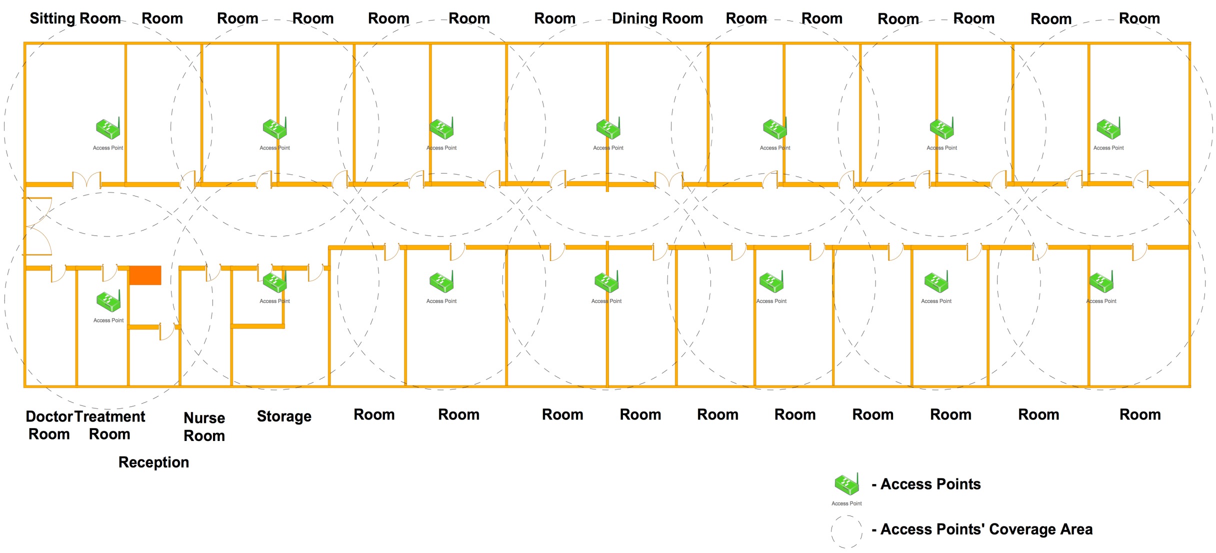

Fig. 2. Illustration of a hospital infirmary used in the construction of the simulation scenario

All the results were obtained in experiments lasting 1000 simulation time units (seconds). In order to get representative and meaningful results the batch means method was used [29]. Then, a set of 30 experiments was performed for each result using different seeds for random calculations. The presented results represent the average values of 30 experiments for each scenario under evaluation.

4. Performance Assessment

In this section a careful study over the influence of sensor nodes velocity and the number of sensor nodes in their connectivity to the network is performed. The present study also focuses attention on the number of messages exchanged between all the network elements and the energy spent on that process.

Time-to-live (TTL) value is one of the main configuration parameters used in all handover approaches described in section 2. This parameter is used in different ways by all the studied handover approaches. Next, all the approaches under evaluation in this work and the influence of TTL value in all of them are summarized.

Hand4MAC - in this approach the network elements (sensor nodes and APs) follow the algorithms described in [23]. More details about this method can be found in [23] and [10]. In this approach the TTL value represents the interval for sensor nodes to revalidate their registration with the associated AP.

RSSI-based - this approach follows the principles used in [17], [16], and [20]. In this approach the TTL value represents the interval to exchange messages between sensor nodes and APs to monitor the RSSI value.

Backbone-based - this approach follows the principles used in [14], [21], and [22]. In this approach the TTL value represents the interval to exchange messages between sensor nodes and APs to monitor the RSSI value.

4.1. Results Analysis for Six Sensor Nodes Considering Different Moving Velocities

The first experiment demonstrates the influence of the velocity of sensor nodes in their network connectivity. This experiment was performed using 6 sensor nodes travelling randomly around the scenario area with velocities of 2 meters per second (mps), 3 mps, 5 mps, and 10 mps. For all the handover mechanisms under evaluation a TTL value of 5 simulation time units was used. For the RSSI-based and the Backbone-based approaches a RSSI threshold value correspondent to 4 meters away from the AP was considered. This experiment lasted 1000 simulation time units.

Fig. 3 presents the average time, in percentage, that 6 sensor nodes travelling at velocities of 2 m/s, 3 m/s, 5 m/s, and 10 m/s remain accessible to the network using the three handover methods under evaluation. As can be observed, Hand4MAC ensures a percentage of connection time above 90% for all the velocities considered except for 10 m/s that remains at about 85%. For the RSSI-based the best value stays at 88% for a velocity of 2 m/s. This value drops to 83% at a velocity of 3 m/s and 72% at a velocity of 5 m/s. For a velocity of 10 m/s this method only ensures a connection to the sensor nodes about 55% of the time. In the case of the Backbone-based solution the connection time simply remains at 72% for 2 m/s, 67% for 3 m/s, 56% for 5 m/s, and 40% for 10 m/s.

The time to perform a handover and the number of handovers performed for each one of the methods is presented in Fig. 4. This figure shows that Hand4MAC performs very fast handovers, around 0.05 seconds, for all sensor nodes' velocities considered. Looking at the number of handovers performed, for a velocity of 2 m/s this number is about 45 handovers. Then this value increases due to rising sensor nodes' velocity, to about 58 handovers at 3 m/s, 87 handovers at 5 m/s, and 129 handovers at 10 m/s. With the RSSI-based solution, the handover time varies from 1.1 seconds for 2 m/s to about 9 seconds for 10 m/s. The number of handovers performed, in this case, decreases with rising sensor nodes' velocity from about 180 handovers for 2 m/s to about 135 handover for 10 m/s. This behavior is related to the fact that the velocity of the sensor nodes prevents a handover decision within a valid interval. In the Backbone-based case, due to the nature of the solution, it can perform very few handover decisions in a valid time interval. In addition, the handovers that can be performed take over 100 seconds to conclude for all the velocities under appreciation.

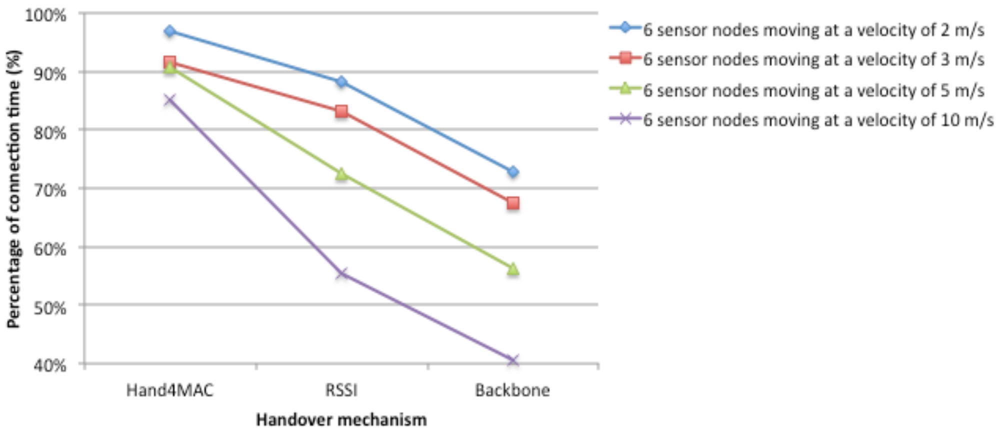

Fig. 3. Percentage of time considering the Hand4MAC, RSSI-based, and back-bone based mechanisms that 6 sensor nodes moving at velocities of 2 m/s, 3 m/s, 5 m/s, and 10 m/s remain connected to the network

Fig. 5 presents the number of messages involved in handover processes performed by the three mechanisms (Hand4MAC, RSSI-based, and backbone-based) for 6 sensor nodes travelling at 2 m/s, 3 m/s, 5 m/s, and 10 m/s. As can be observed the number of received messages by Hand4MAC solution is higher than for the other two solutions. But as will be verified further on, this situation inverts when the number of sensor nodes in the scenario increases.

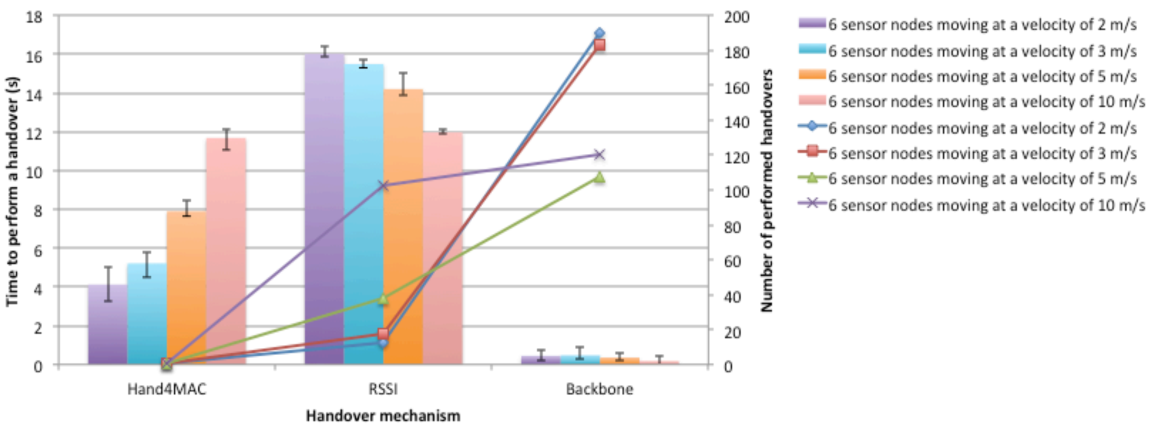

Fig. 4. Number of performed handovers considering the Hand4MAC, RSSI-based, and back-bone based mechanisms when 6 sensor nodes move at velocities of 2 m/s, 3 m/s, 5 m/s, and 10 m/s (column graph) and the time that 6 sensor nodes need to complete a handover process moving at 2 m/s, 3 m/s, 5 m/s, and 10 m/s respectively for the considered handover mechanisms (line graph)

Fig. 6 depicts the energy consumption on the number of messages used by the three handover methods for 6 sensor nodes traveling at 2 m/s, 3 m/s, 5 m/s, and 10 m/s. The energy values were based on the CC2420 working parameters [28]. For message reception CC2420 spends about 18.8 milliamps (mA) and 17.4 mA for transmitting. These values were then operated with the number of messages involved in handover processes and converted to energy consumption in watts (W).

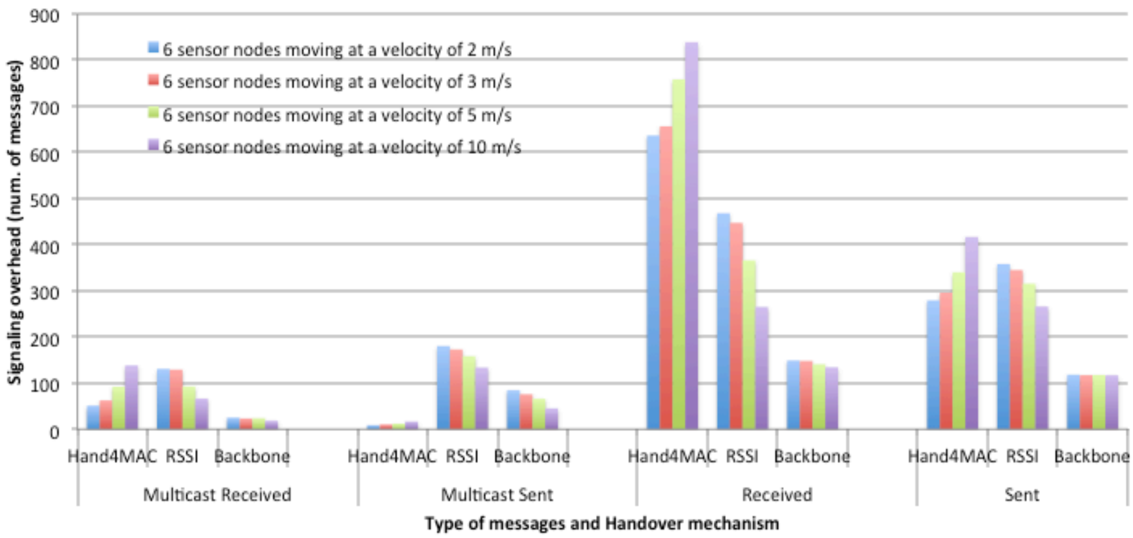

Fig. 5. Number of multicast received, multicast sent, received, and sent messages considering the Hand4MAC, RSSI-based, and back-bone based mechanisms when 6 sensor nodes move at velocities of 2 m/s, 3 m/s, 5 m/s, and 10 m/s

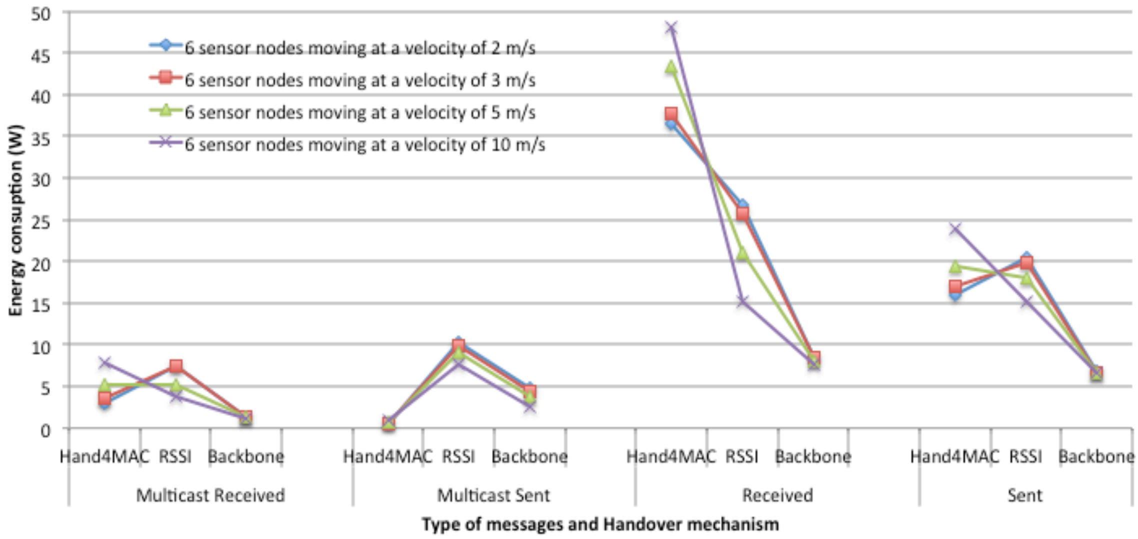

Fig. 6. The amount of energy consumed by multicast received, multicast sent, received, and sent messages considering the Hand4MAC, RSSI-based, and back-bone based mechanisms when 6 sensor nodes move at velocities of 2 m/s, 3 m/s, 5 m/s, and 10 m/s

The energy consumption by Hand4MAC for received messages is higher than for the other solutions under evaluation. As described before it will be seen that this situation will revert when the number of sensor nodes increases. Fig. 7

presents the total energy consumption for the three methods under the same conditions. As can be observed for sensor nodes' velocities of 2 m/s and 3 m/s, Hand4MAC and RSSI-based solutions, spend almost the same energy. However, at these velocities Hand4MAC can ensure over 90% connectivity to the sensor nodes, and RSSI-based only about 85%. For velocities of 5 m/s and 10 m/s the energy consumption increases for Hand4MAC case and decreases for RSSI-based case. However, in this case the percentage of connectivity for RSSI-based drops drastically to about 72% and 55% respectively. Considering Hand4MAC, the connection percentage remains at about 90% and 85% respectively. Backbone-based method is the most economic in terms of energy expenditure. Nevertheless, this solution has very poor results in terms of senor nodes' network connection with no more than 72% for 2 m/s and 40% for 10 m/s. These values are not consistent with a desirable continuous connection to the sensor nodes.

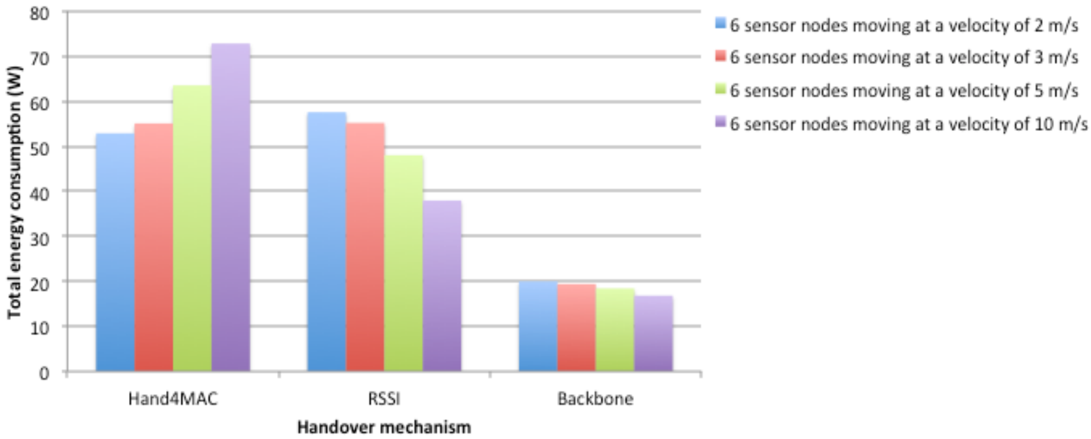

Fig. 7. The total energy consumed considering the Hand4MAC, RSSI-based, and back-bone based mechanisms when 6 sensor nodes move at velocities of 2 m/s, 3 m/s, 5 m/s, and 10 m/s

This experiment proves that Hand4MAC approach can ensure high connectivity to sensor nodes in scenarios where they travel with superior velocities. Therefore this approach could be used for different applications, where the velocity of sensor nodes needs to be increased, with almost the same results in terms of network connectivity.

4.2. Results Analysis Considering Different Quantities of Sensor Nodes Moving at a Velocity of 2 m/s

The next experiment varies the number of sensor nodes in the scenario. This experiment demonstrates the scalability influence of sensor nodes' number in their network connectivity. For this experiment it was considered that all the sensor nodes travel randomly with a velocity of 2 m/s. This value is close to the velocity of a walking person, which can simulate perfectly patients walking around the infirmary. The influence on the network connectivity for a batch of 6, 30, and 50 sensor nodes was evaluated. The TTL value considered was 5 simulation time units and the RSSI threshold value was correspondent to 4 meters away from the AP.

Fig. 8 presents sensor nodes' network connectivity percentage, travelling at 2 m/s, for the three batches under evaluation (6, 30, and 50 sensor nodes). As can be observed, even when the number of sensor nodes increases Hand4MAC can ensure connectivity above 93%. For RSSI-based solution the network connectivity remains around 88% for the three batches. Nevertheless, as will be seen further on, the number of sensor nodes in the scenario influences the energy consumption, increasing it significantly. The network connectivity for Backbone-based solution drops from 72% using a batch of 6 sensor nodes to only 53% using a batch of 50 sensor nodes.

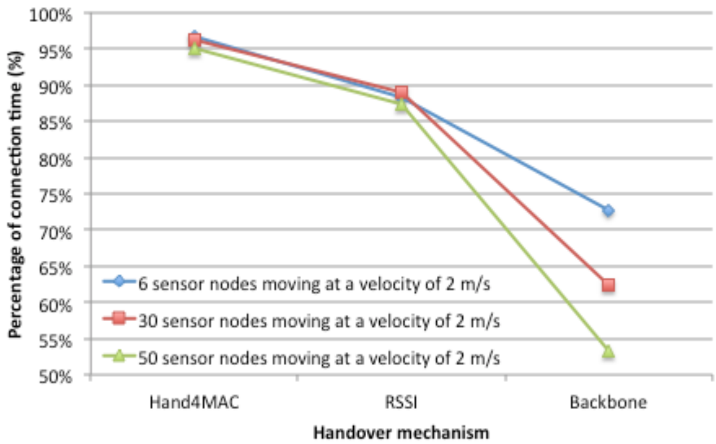

Fig. 8. Percentage of time considering the Hand4MAC, RSSI-based, and back-bone based mechanisms with 6 sensor nodes, 30 sensor nodes, and 50 sensor nodes moving at a velocity of 2 m/s remain connected to the network

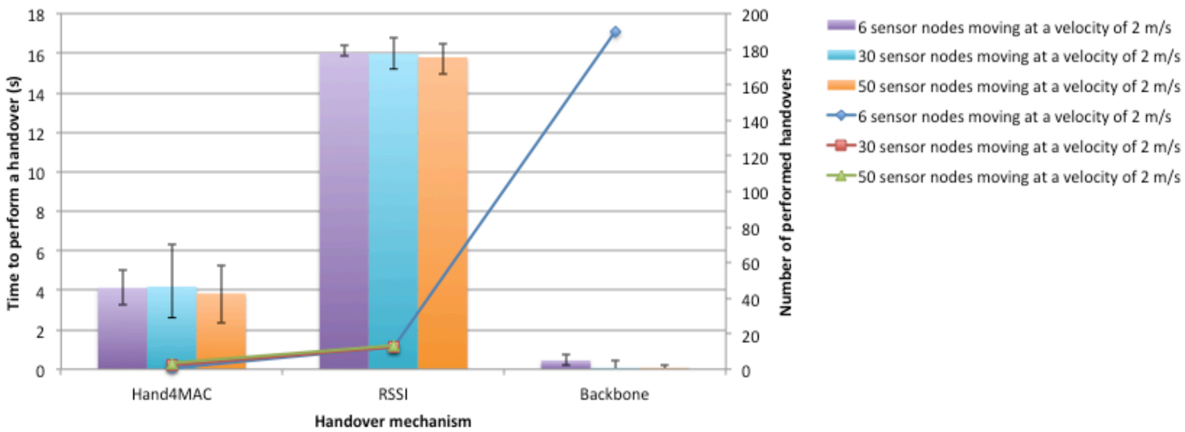

Fig. 9. Number of performed handovers considering the Hand4MAC, RSSI-based, and back-bone based mechanisms when 6 sensor nodes, 30 sensor nodes, and 50 sensor nodes move at a velocity of 2 m/s (column graph) and the time that 6 sensor nodes, 30 sensor nodes, and 50 sensor nodes need to complete a handover process moving at 2 m/s respectively for the considered handover mechanisms (line graph)

Fig. 9 depicts both the time needed to perform a handover for the same three batches of sensor nodes (6, 30, and 50 sensor nodes) traveling at 2 m/s using the three handover methods and the number of handovers performed by each one of the handover methods under the same conditions. As observed, the times needed to perform a handover are very close for all batches of sensor nodes using Hand4MAC, around 0.2 seconds. The same behavior can be found using RSSI-based solution, but in this case the values are around 1.1 seconds. For the Backbone-based it was only possible to obtain the time value for the experiment that uses a batch of 6 sensor nodes which is around 17 seconds. For the other two batches, it was not possible to collect this value because most sensor nodes performed no handovers at all. This situation occurs because the number of sensor nodes influences the time needed to decide the handover process and therefore the decision is not taken within a valid interval. The number of handovers performed using Hand4MAC is very close for the three batches, around 44. This value is significantly small compared to RSSI-based value of 180. As can be seen for the Backbone-based solution, the number of handovers is insignificant.

The number of messages exchanged between the network elements is directly related to the energy consumption. Fig. 10 demonstrates the number of messages received and sent by the three batches of sensor nodes using different handover methods, while Fig. 11 presents the energy consumption expended by all those messages.

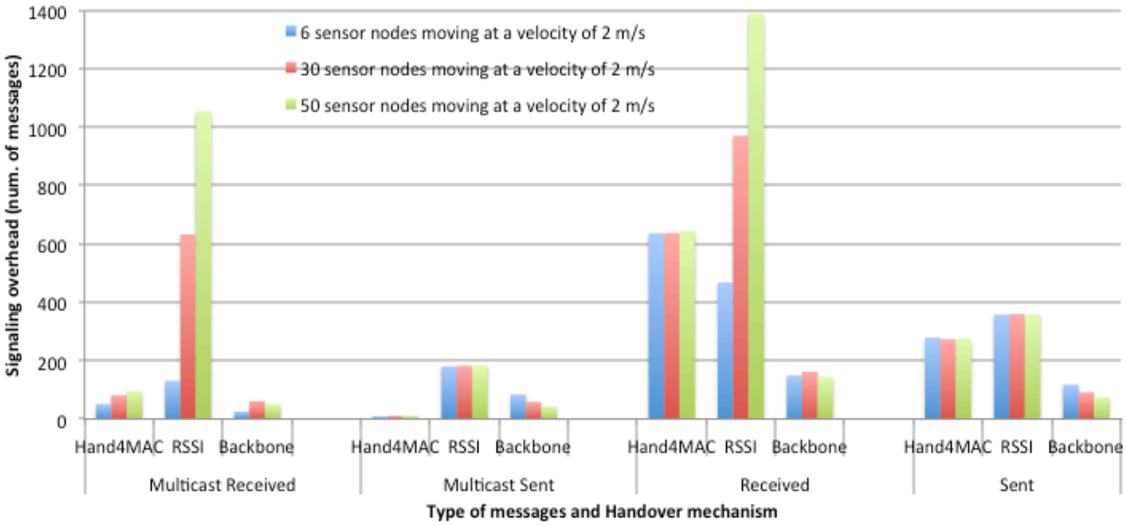

Fig. 10. Number of multicast received, multicast sent, received, and sent messages considering the Hand4MAC, RSSI-based, and back-bone based mechanisms when 6 sensor nodes, 30 sensor nodes, 50 sensor nodes move at a velocity of 2 m/s

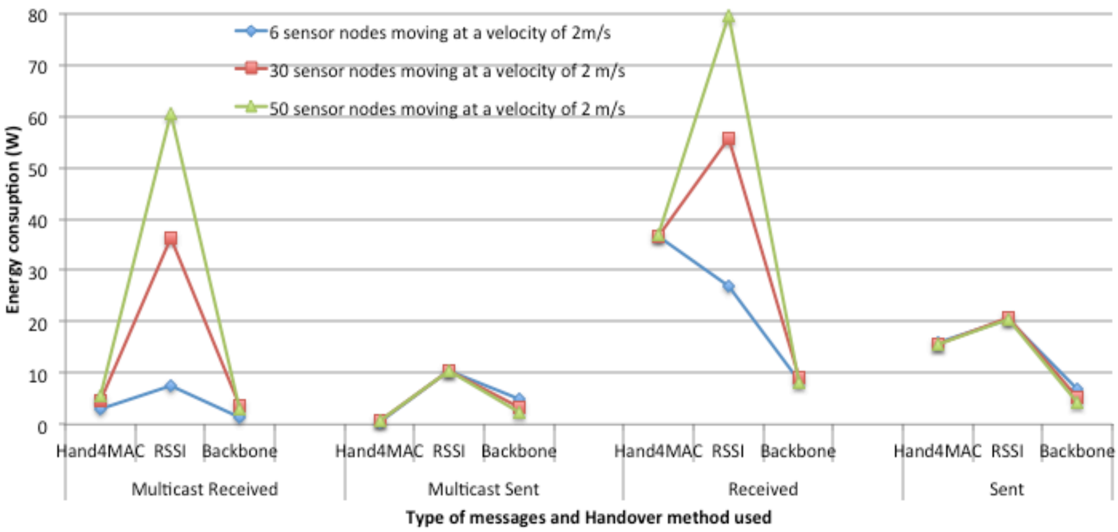

Fig. 11. The amount of energy consumed by multicast received, multicast sent, received, and sent messages considering the Hand4MAC, RSSI-based, and back-bone based mechanisms when 6 sensor nodes, 30 sensor nodes, and 50 sensor move at a velocity of 2 m/s

Fig. 12 depicts the total energy consumption spent by Hand4MAC, RSSI-based, and Backbone-based solutions during the three experiments using the three batches of sensor nodes. For Hand4MAC it can be seen that the number of sensor nodes in the scenario does not influence the total energy consumption, which remains around 53 watts for a percentage of connectivity to the sensor nodes of around 91%. Considering RSSI-based, the energy consumption increases from around 58 watts using 6 sensor nodes, to about 111 watts using 50 sensor nodes, allowing only a percentage of connectivity to the sensor nodes of about 88%. Using the Backbone-based solution the energy consumption is substantially smaller, around 17 watts. Nevertheless, this solution drops the connectivity percentage of sensor nodes from 72% using a batch of 6 sensor nodes to 53% using a batch of 50 sensor nodes.

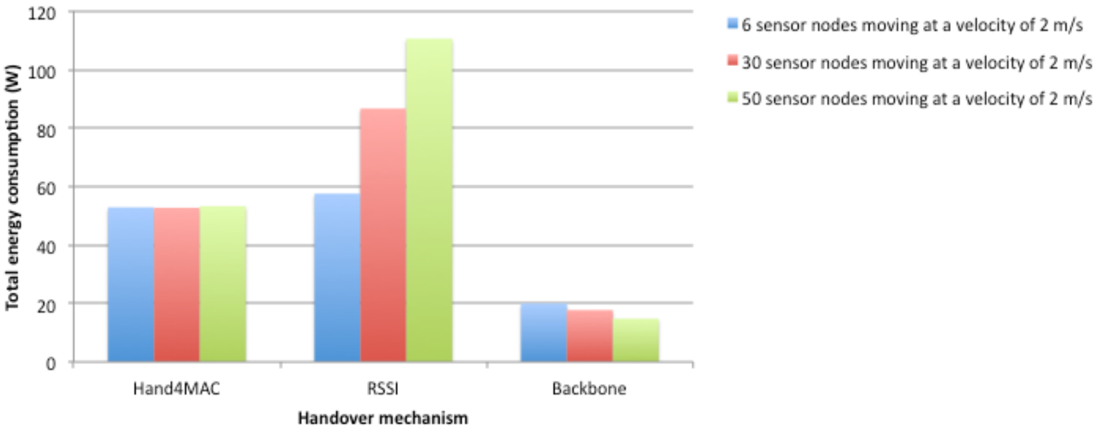

Fig. 12. The total energy consumed considering the Hand4MAC, RSSI-based, and back-bone based mechanisms when 6 sensor nodes, 30 sensor nodes, and 50 sensor nodes move at a velocity of 2 m/s

4.3. Results Analysis Considering Different Quantities of Sensor Nodes Moving at Velocities of 3 m/s and 5 m/s

The next experiment presents the relationship between increasing the velocity of the sensor nodes and increasing the number of sensor nodes in the simulation scenario. This experiment evaluates the application of these handover methods in situations that need faster sensor node mobility. Two situations were considered. First with sensor nodes traveling at a constant velocity of 3 m/s while in the second situation the velocity of the sensor nodes was increased to 5 m/s. In all cases batches of 6, 30, and 50 sensor nodes were tested. The same TTL value of 5 simulation time units was used for all the handover solutions. The RSSI value considered for the RSSI-based and the Backbone-based approaches was correspondent to 4 meters away from the AP. Fig. 13 and Fig. 14 show that increasing the velocity and the number of sensor nodes in the scenario does not influence the percentage of time that the sensor nodes remain accessible to the network using Hand4MAC and RSSI-based solutions. However using Hand4MAC this value remains at about 90% while in the case of RSSI-based this value drops from around 83% to 72% when sensor nodes travel at 3 m/s and 5 m/s respectively. In the case of the Backbone-based solution the number of sensor nodes and their velocity drastically influence the percentage of time connectivity. This value drops from 67% for a batch of 6 sensor nodes travelling at 3 m/s to about 25% for a batch of 50 sensor nodes travelling at 5 m/s.

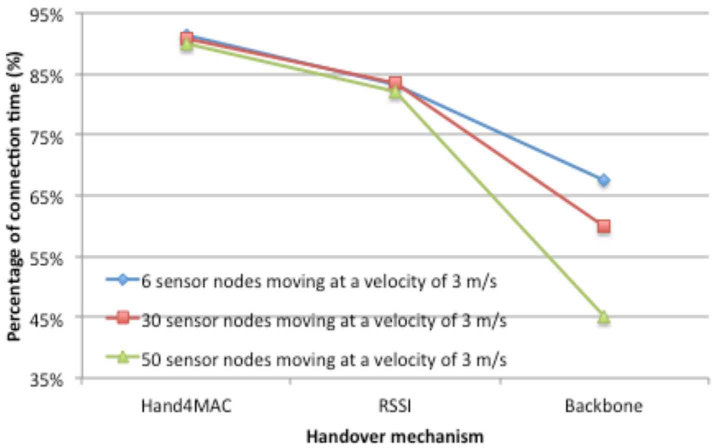

Fig. 13. Percentage of time considering the Hand4MAC, RSSI-based, and back-bone based mechanisms with 6 sensor nodes, 30 sensor nodes, and 50 sensor nodes moving at a velocity of 3 m/s remain connected to the network

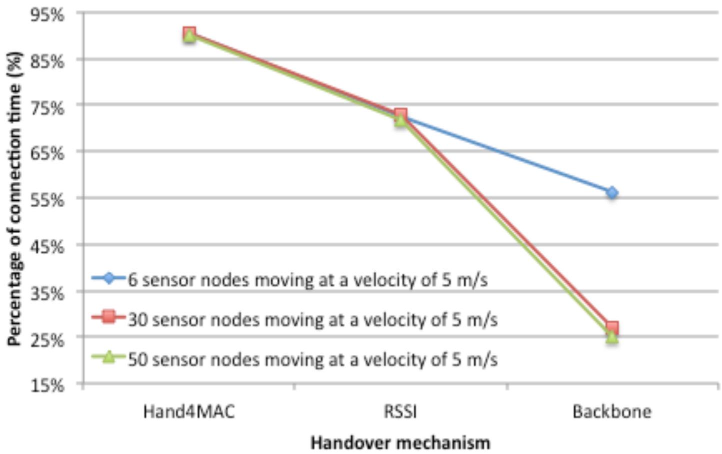

Fig. 14. Percentage of time considering the Hand4MAC, RSSI-based, and back-bone based mechanisms when 6 sensor nodes, 30 sensor nodes, and 50 sensor nodes moving at a velocity of 5 m/s remain connected to the network

Regarding Fig. 15 and Fig. 16 it can be observed that the number of performed handovers increases from around 57 at a velocity of 3 m/s to about 95 at a velocity of 5 m/s using the Hand4MAC solution. When using the RSSI-based solution this value stays practically the same, at about 160 for the two velocities. These figures also depict the time needed to perform a handover. This value is very small for the Hand4MAC solution compared with the RSSI-based solution. In the RSSI-based solution this value rises from 1.7 seconds at 3 m/s to 3.7 seconds at 5 m/s while in the Hand4MAC this value remains at around 0,3 seconds for the two velocities. For the Backbone-based it was only possible to obtain the time values for the experiment that used a batch of 6 sensor nodes which is around 17 seconds at 3 m/s and 10 seconds at 5 m/s. For the other two batches, it was not possible to collect this value because most sensor nodes perform no handovers at all as can be observed by the column graph in Fig. 15 and Fig. 16. This situation occurs because the number and the velocity of sensor nodes influence the time needed to decide on the handover process and therefore the decision is not made within a valid interval.

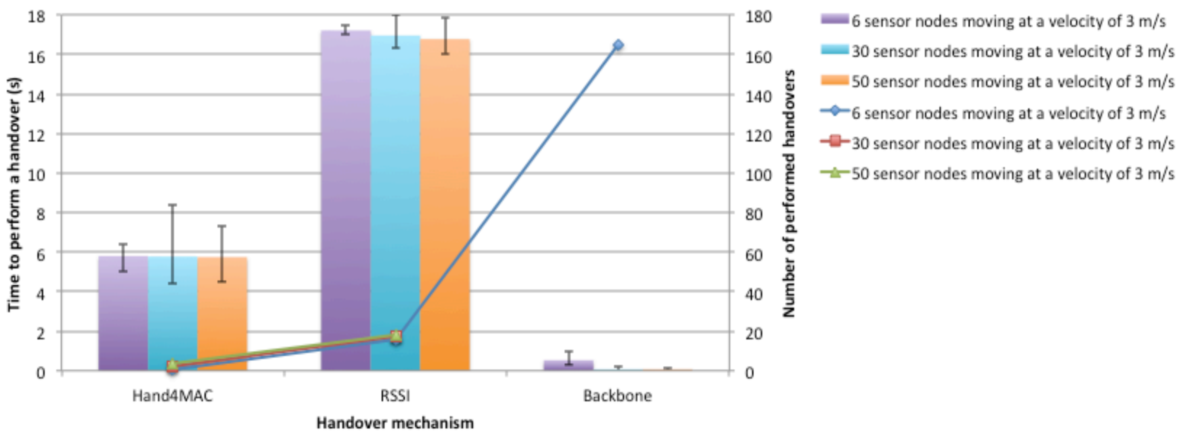

Fig. 15. Number of performed handovers considering the Hand4MAC, RSSI-based, and back-bone based mechanisms when 6 sensor nodes, 30 sensor nodes, and 50 sensor nodes move at a velocity of 3 m/s (column graph) and the time that 6 sensor nodes, 30 sensor nodes, and 50 sensor nodes need to complete a handover process moving at 3 m/s respectively for the considered handover mechanisms (line graph)

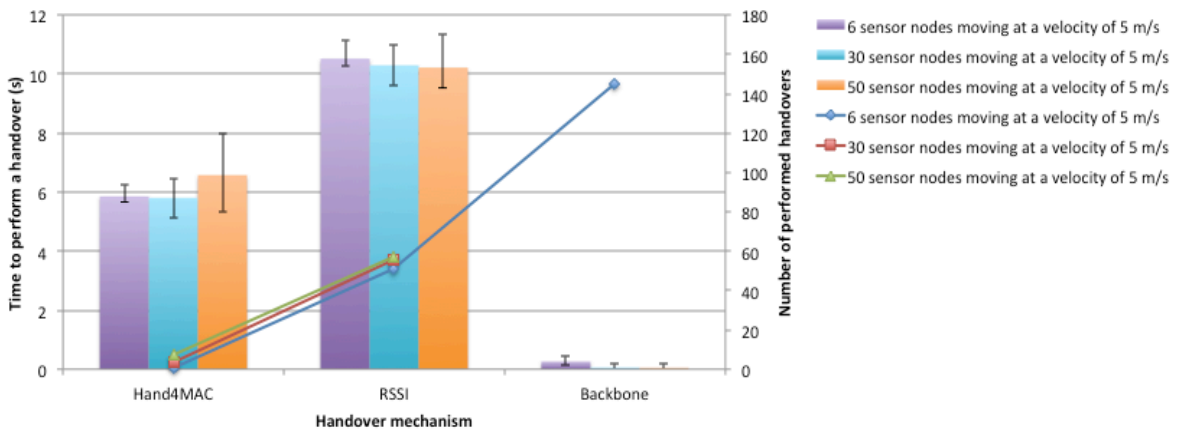

Fig. 16. Number of performed handovers considering the Hand4MAC, RSSI-based, and back-bone based mechanisms when 6 sensor nodes, 30 sensor nodes, and 50 sensor nodes move at a velocity of 5 m/s (column graph) and the time that 6 sensor nodes, 30 sensor nodes, and 50 sensor nodes need to complete a handover process moving at 5 m/s respectively for the considered handover mechanisms (line graph)

The number of messages sent and received by the sensor nodes travelling at 3 m/s and 5 m/s is presented in Fig. 17 and Fig. 18 respectively. As can be seen the RSSI-based solution significantly increases the multicast received messages when the number of sensor nodes increases. This behavior is also observed for received messages. Using the Hand4MAC method the number of messages exchanged does not vary with the number of sensor nodes present in the scenario. For the Backbone-based method the number of messages exchanged is very small when compared with the other two approaches, although, as previously seen the percentage of connection to sensor nodes is very poor when using this solution.

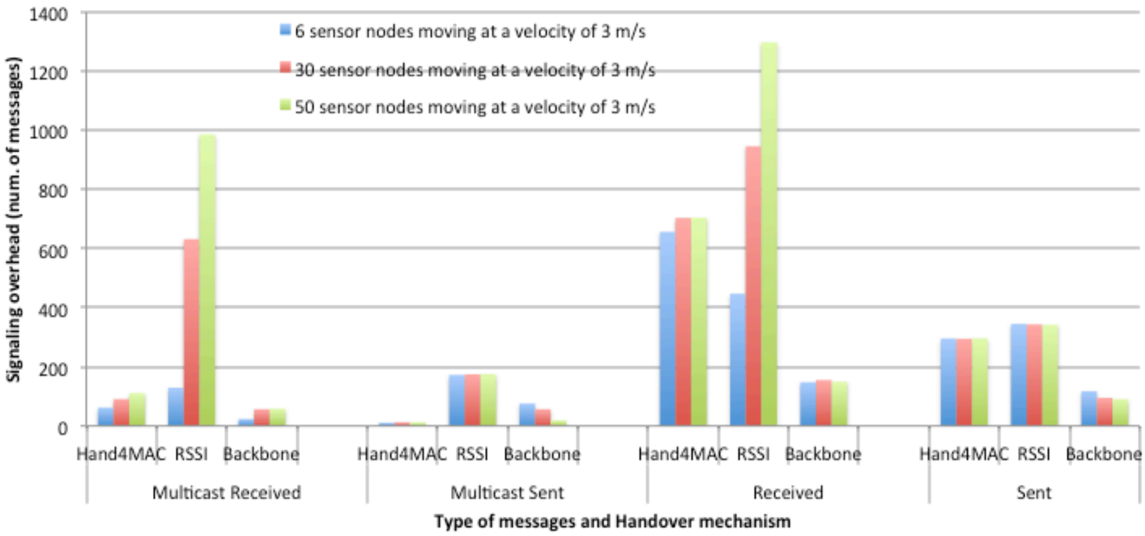

Fig. 17. Number of multicast received, multicast sent, received, and sent messages considering the Hand4MAC, RSSI-based, and back-bone based mechanisms when 6 sensor nodes, 30 sensor nodes, 50 sensor nodes move at a velocity of 3 m/s

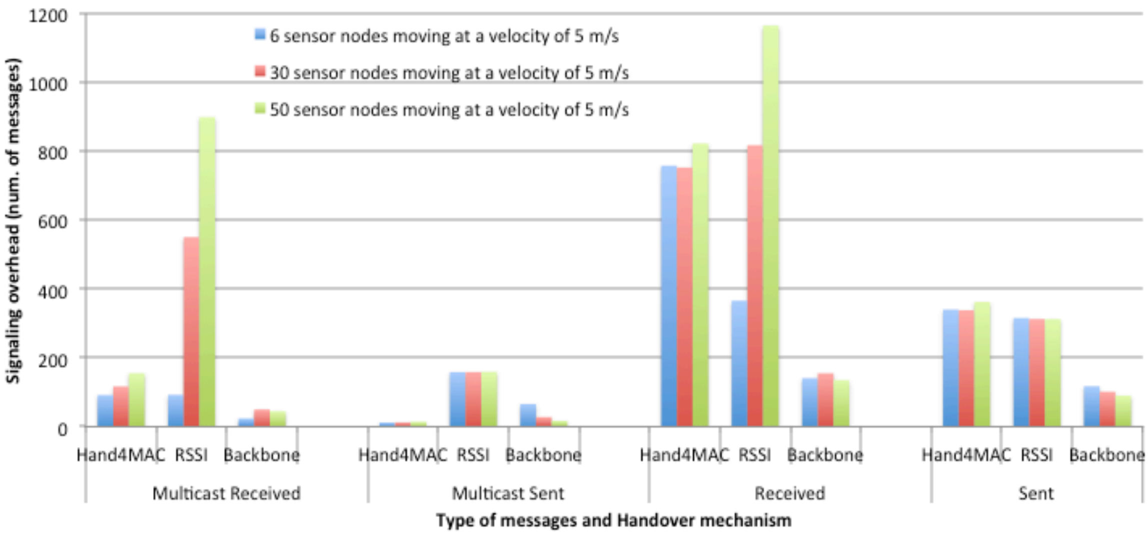

Fig. 18. Number of multicast received, multicast sent, received, and sent messages considering the Hand4MAC, RSSI-based, and back-bone based mechanisms when 6 sensor nodes, 30 sensor nodes, 50 sensor nodes move at a velocity of 5 m/s

Regarding the energy consumption, Fig. 19 and Fig. 20 present these values focusing on each message type for all three handover methods. An overview of total energy consumption is depicted in Fig. 21 and Fig. 22. These figures demonstrate that the Backbone-based solution consumes less energy when compared with the other two solutions, but as previously proven, this solution only ensures very poor connectivity to sensor nodes. Whereas the energy consumption does not change much in the Hand4MAC method when the number of sensor nodes is increased. Using the RSSI-based solution the energy consumption increases a lot when the number of sensor nodes increases.

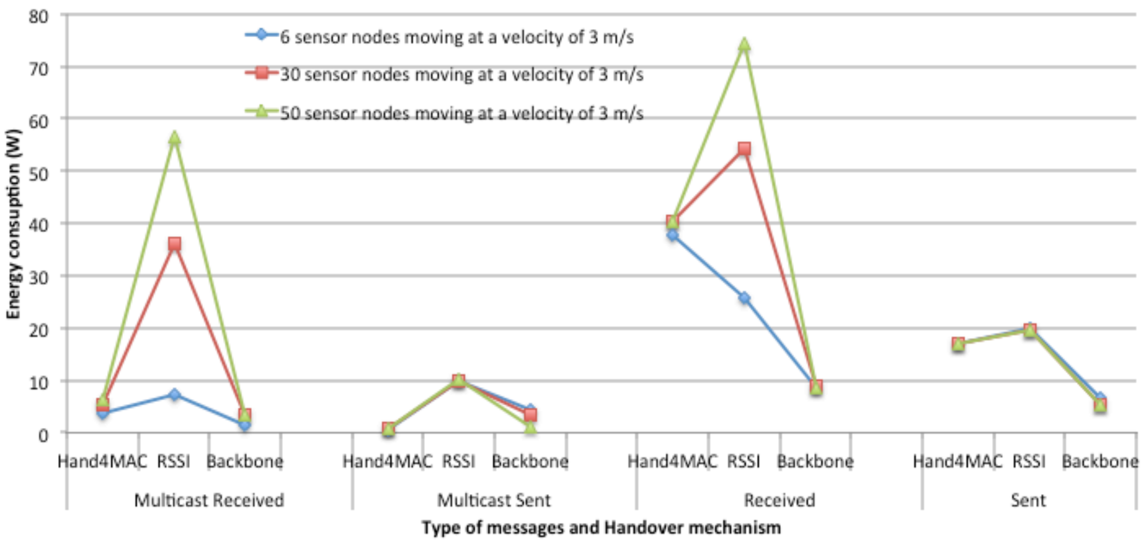

Fig. 19. The amount of energy consumed by multicast received, multicast sent, received, and sent messages considering the Hand4MAC, RSSI-based, and back-bone based mechanisms when 6 sensor nodes, 30 sensor nodes, and 50 sensor move at a velocity of 3 m/s

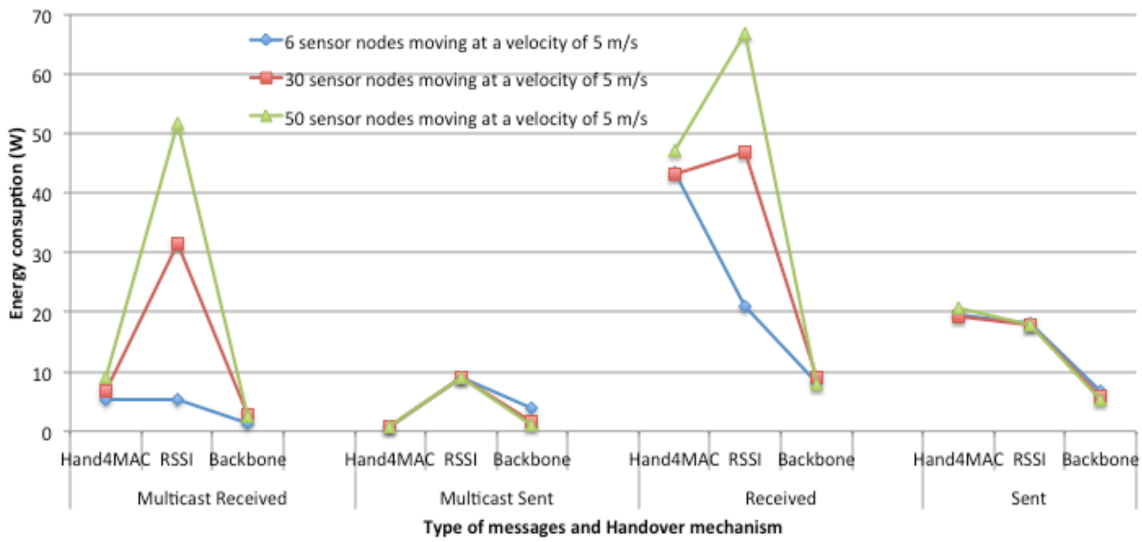

Fig. 20. The amount of energy consumed by multicast received, multicast sent, received, and sent messages considering the Hand4MAC, RSSI-based, and back-bone based mechanisms when 6 sensor nodes, 30 sensor nodes, and 50 sensor move at a velocity of 5 m/s

Looking at these results it can be concluded that the number of sensor nodes in the scenario does not interfere with their connectivity to the network using the Hand4MAC method. In all the experiments performed this value always remains above 90%~92%, which can be considered as an almost continuous connection. In addition, the number of sensor nodes in the scenario did not interfere with the overall energy consumption using this method. It has been proven that for the RSSI-based method when the number of sensor nodes increases, the network connectivity decreases and the energy consumption increases significantly. The RSSI-based method can in the best-case reach 88% of network connectivity for a very small batch of sensor nodes (6 sensor nodes). The Backbone-based solution proves to be the weakest method to ensure continuous connection to the sensor nodes in this scenario. The best result obtained by this solution, about 72%, was obtained with a very small batch of sensors (6 sensor nodes) travelling at 2 m/s. In all the other experiments (with 30, and 50 sensor nodes) the network connectivity for this solution drops to under 65%.

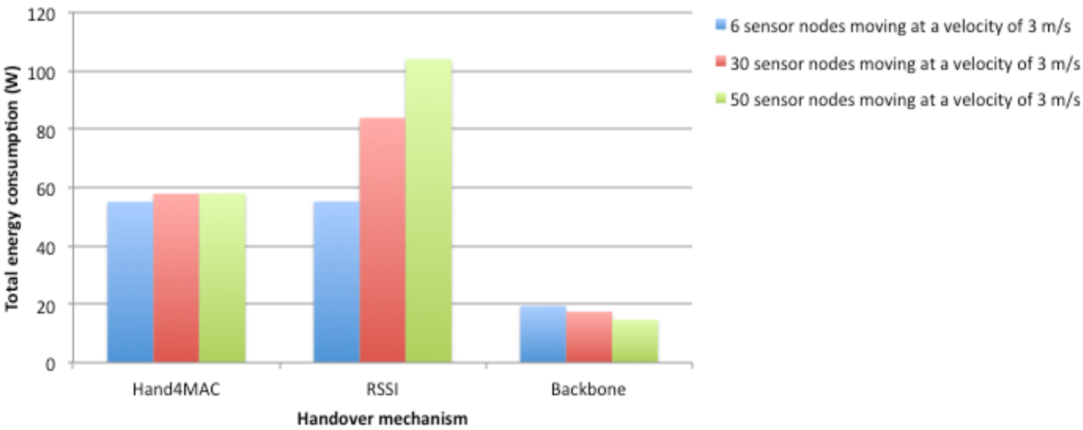

Fig. 21. The total energy consumed considering the Hand4MAC, RSSI-based, and back-bone based mechanisms when 6 sensor nodes, 30 sensor nodes, and 50 sensor nodes move at a velocity of 3 m/s

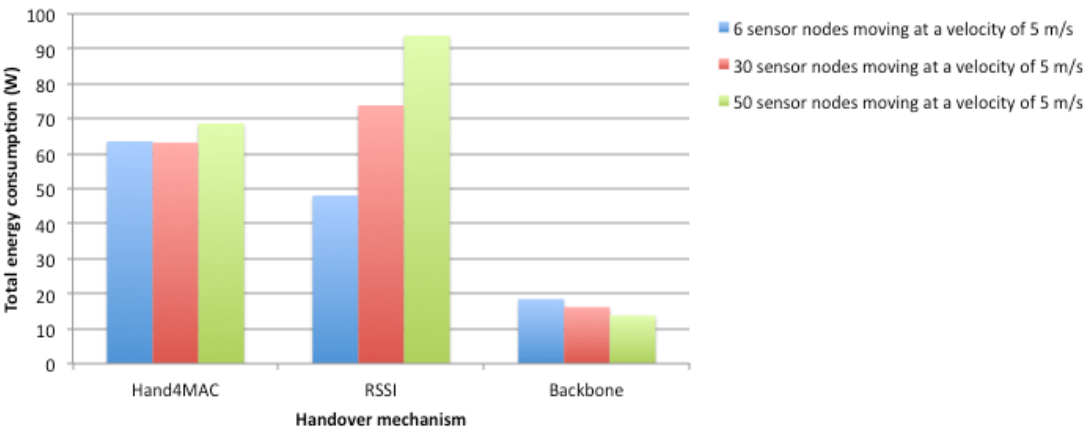

Fig. 22. The total energy consumed considering the Hand4MAC, RSSI-based, and back-bone based mechanisms when 6 sensor nodes, 30 sensor nodes, and 50 sensor nodes move at a velocity of 5 m/s

5. Conclusion and Future Work

In this paper the influence of the number of sensor nodes and their velocity in the network connectivity, number of exchanged messages, and energy consumption for three handover methods, Han4MAC, RSSI-based, and backbone-based were analyzed. This work evaluated the available approaches in order to find the best solution to support continuous monitoring of hospitalized patients. Several experiments were performed using a simulation scenario that emulates a hospital infirmary considering real-time and continuous access to the sensor nodes carried by the patients. It was found that the Hand4MAC can ensure percentages of connectivity to the sensor nodes above 90% in all cases, while the other two solutions can not improve on 88%. Moreover, this value drops significantly when the number of sensor nodes escalade. It was also demonstrated that the Hand4MAC solution consumes little energy and that this consumption is not influenced by the number of sensor nodes used.

The results demonstrated in this paper encouraged the authors to deploy the Hand4MAC method in a real hospital ward as part of future research works. The evolution and enhancement of this method is also part of future work.

Acknowledgments

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Chapter 7

Performance Assessment of a New Intra-Mobility Solution for Healthcare Wireless Sensor Networks

This chapter consists of the following article:

Performance Assessment of a New Intra-Mobility Solution for Healthcare Wireless Sensor Networks

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Performance assessment of a new intra-mobility solution for Healthcare Wireless Sensor Networks

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Abstract: The use of Wireless Sensor Networks (WSNs) in healthcare is a key issue. These technologies can improve the way patients are monitored in an infirmary or a hospital. The Healthcare WSNs (HWSNs) assume the use of WSNs for health support, collecting and send patients' health parameters wirelessly to remote monitoring systems. These applications bring many new challenges to traditional WSNs. These challenges include the continuous support connectivity to mobile nodes. The ability to let patients moving around when hospitalised is important to promote their quality of life. Managing the transitions of access points' attachment when a node moves across several coverage areas is on top of research topics in HWSNs. This paper studies the performance of a new handover mechanism to support intra-mobility of nodes for HWSN, called Hand4MAC. The evaluation is performed through a laboratory testbed and it was compared to the most used handover solutions. The results shown that Hand4MAC is more efficient in number of exchanged messages and it could ensure almost continuous connection to the nodes.

Keywords: HWSNs; healthcare wireless sensor networks; WSNs; wireless sensor networks; handover; intra-mobility; mobility support.

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1 Introduction

Mobility support of sensors nodes in Wireless Sensor Networks (WSNs) is increasing the applicability of these technologies to new fields. In healthcare facilities, for example, these technologies can be used to monitor patients giving the ability to move freely around a WSN-covered area (Pantelopoulos and Bourbakis, 2010; Bradai et al., 2011). HWSNs (Alemdar and Ersoy, 2010) are based on mobile sensor nodes attached to patients able to collect body parameters and send them wirelessly to access points (APs). The APs are used to provide network coverage in all the perimeter of the monitored area. Mobility of sensor nodes despite having brought new applications to the WSNs have also brought lots of new challenges (Dong and Dargie, 2012). One of the main challenges introduced in WSNs giving the ability to sensor nodes moving around is the network coverage. The available area in healthcare facilities for patients to move around can change from tens to hundreds of metres. To cover all these areas, several APs should be used. To maintain connectivity to the sensor nodes, they should be connected to an AP all the time (Diallo et al., 2012). In mobile scenarios where the sensor nodes can move between different APs' coverage areas, it is important to determine the exact moment to change the connection to a new AP. If it is possible to predict the exact moment the sensor node will lose connection to an AP and it can change to a new one before that happens, it can be ensured a continuous communication to the sensor nodes. Continuous communication to the sensor nodes is important in systems for life support, such as HWSNs (Neves et al., 2008). The process of changing the connection between APs by the sensor nodes is known as handover process. This paper focuses on performance assessment of a new method for handover, allowing continuous connection to the sensor nodes, named Hand4MAC. This method was proposed in Caldeira et al. (2012a). The sensor nodes used in HWSNs are tiny devices with limited resources. This characteristic should be considered in the construction of handover mechanisms. Small batteries power the sensor nodes from one day to more than a week depending on the optimisation of the processing tasks. A wireless module compliant with IEEE 802.15.4 standard ensures the communication with these sensor nodes. Furthermore, the processing power available in these sensors nodes is limited.

Normally, healthcare facilities use the same network domain in their overall area. Therefore, this proposal encloses only the support for intra-mobility of sensor nodes. Intra-mobility is characterised by the need of changing the point of attachment to the network but always using the same Internet Protocol (IP) address (Rodrigues and Neves, 2010). HWSNs promote the health control of human beings giving them the possibility to move around so that it can improve the quality-of-life of these patients when hospitalised. But, it is important to keep these patients under monitoring even when they are moving. Most of the health parameters need a close control to detect abnormal situations. The accuracy of the control over these parameters may be the difference between life and death. So, the HWSNs should support continuous access to the sensor nodes carried by patients to promote a close control. The solution proposed in this paper tries to keep a continuous access to the sensor nodes even when they cross several APs' coverage areas.

The main contributions of the paper are the following:

- presentation of a new intra-mobility solution for continuous monitoring of patients' health parameters using an HWSN, called Hand4MAC
- performance evaluation and demonstration of the new intra-mobility solution in a laboratory testbed.

The remainder of this paper is organised as follows. Section 2 focuses on the most significant approaches available in the literature about mobility solutions in WSNs. Section 3 addresses the method to get connection probability based on an available propagation model while Section 4 describes the new handover mechanism and all its related considerations. The testbed construction and deployment are described in Section 5. Section 6 presents a performance assessment study of this proposal in a laboratory testbed. Finally, Section 7 concludes the paper and points out some future work to optimise this approach.

2 Background

Recent advances in WSN applications require that the sensor nodes become mobile. Most of the solutions for WSN applications use static sensor nodes. Recently, some approaches have proposed the use of mobile nodes. Next, it is presented the most recent approaches for WSNs with mobility support of sensor nodes regarding handover technologies.

In Zinonos and Vassiliou (2010), a new intra-mobility approach for WSNs is presented. It is based on a mobile solution for 6LoWPAN (Ko et al., 2011) using a proxy agent technology. The proposed procedure for supporting intra-mobility of sensor nodes works as follows: the current proxy agent monitors the Received Signal Strength Indicator (RSSI) value of the connection with the sensor node. A predefined RSSI threshold is always compared with the actual RSSI value. If this value drops below the threshold, then the current proxy agent informs the neighbourhood proxy agents to start hearing for that sensor node. If a surrounding proxy agent receives packets from this sensor node, this proxy agent prepares a message (join message) with the sensor node's address and the RSSI value received and sends it to the parent proxy agent. The parent proxy agent when receives this message verifies if the RSSI value is acceptable and if the sensor node's address is the same. If the verification is correct, it will answer (join acknowledge message) to the proxy agent with an accept message. If there are several surrounding proxies, the parent proxy can receive more than one join message. At this time, the parent proxy chooses the one with better RSSI value. The new proxy agent notifies the edge router (gateway) that this sensor node now is reachable by him or her. The previous proxy agent informs the sensor node about its new attachment point. This solution needs continuous exchange messages between the sensor node and the current proxy agent to control the RSSI value and decide the right moment to start looking for a new proxy. The processing of all these messages contributes to increased energy expenditure. Considering that sensor nodes batteries have limited resources, it is important optimising the signalling costs to support sensor nodes' mobility. This approach, also, assumes that APs are able to communicate with each other.

Fotouhi et al. (2010) described a reliable handover procedure to support mobile sensor nodes in WSNs. To evaluate the handover decision, this proposal uses a set of metrics. These metrics are RSSI level, velocity of the mobile sensor, number of hops to reach the AP, traffic load, energy level and link quality value. To evaluate all these metrics, a Fuzzy-Link Quality Estimator (F-LQE) presented in Baccour et al. (2010) is used. This procedure proposes the use of two phases to evaluate the handover needed. In the first phase, the decision for handover or not is taken. At this phase, the sensor nodes periodically send probe messages to their attached APs and the APs reply with an acknowledge message to the sensor nodes. The RSSI average of these messages and the velocity of the sensor nodes are used by the F-LQE to determine the handover needing. This procedure assumes that velocity of the sensor nodes can be unknown. This way, only the RSSI average is used to take the decision to handover or not. In this case, the RSSI average is compared with a predefined threshold. If the average value is below this threshold, then the decision is to handover. Whether the decision of phase 1 is to handover the mechanism proceeds to phase 2. In phase 2, it is decided the best new AP to attach to. The sensor nodes at this phase start sending periodic probe messages (multicast messages) to all their surrounding APs. In a short time, the sensor nodes start to receive the acknowledge messages from the APs in their vicinity. At this phase, the sensor nodes evaluate not only the RSSI value but also a set of APs specific parameters like traffic load, depth and energy level. All these parameters from all the surrounding APs are then used as inputs to F-LQE to estimate the best choice to attach to. In this solution, the decision to handover is based on a close monitoring to the RSSI value between sensor nodes and APs. To perform the monitoring task, these two elements are continuously exchanging messages. This process increases a lot the signalling costs and the energy consumption to maintain the connectivity with the sensor nodes. Moreover, all the procedure is performed in the sensor nodes' side that increases even more the energy consumption.

Silva et al. (2012a, 2012b) proposed a proxy-based mobility scheme for WSNs. This proposal is based on the concept of Network of Proxies (NoPs). Several proxies are spread throughout the monitored region. These proxies are interconnected with a shared backbone. Each proxy cares about the connection to the sensor nodes within its coverage area. The proxy always monitors the link quality with the sensor nodes that it cares about. If the proxy detects deterioration on a link quality with a certain sensor node, it informs its neighbour proxies to look for this sensor node. When a neighbour proxy receives a message by this sensor node, it notifies the previous proxy. The previous proxy then decides that the sensor node should handover to the neighbour proxy with better link quality. After this, the previous proxy informs the new proxy about the selection and the new proxy starts to care about this sensor node. This solution needs a close monitoring to the link quality between the sensor nodes and the proxies. This monitoring is obtained by continuous exchanging messages, which contributes for a significant cost in signalling process to support handover decisions.

In Petajajarvi and Karvonen (2011), the authors proposed a handover solution for WSNs supported by 6LoWPAN (SH-WSN6). This proposal allows the sensor nodes to be connected with more than one AP at the same time. To support this solution, a remote resource directory (RD) that contains the information about all the interfaces that can reach each sensor node in the WSN is needed. The APs are always sending router advertisement (RA) messages. If a sensor node receives one of this RA, it checks if it is already connected with this AP or not. If not, the sensor node replies with a connection confirmation and the APs inform the RD about the new route to this sensor node. To maintain the routes up-to-date, the decision to remove an AP connection is based on the ratio of received RA messages from that AP. It is assumed that all APs send RA messages at the same rate. RA messages are multicast messages and, therefore, they are not very efficient in terms of energy consumption. This solution bases its operation on an intensive use of RA messages. Also, this solution considers that if the interval used between RA messages is too short, it increases unnecessarily the signalling costs in the network and, therefore, reducing the lifetime of the sensor nodes. Otherwise, if this interval is too large, it allows that the sensor nodes can be inaccessible between RA messages, which is incompatible with continuous communication to the sensor nodes.

GinMAC is an extension to IEEE 802.15.4 standard that supports intra-mobility of sensor nodes in WSNs. This approach was proposed by Jara et al. (2011) and also used by Zinonos et al. (2011). GinMAC tries to keep good link quality to the sensor nodes by monitoring the RSSI values exchanged messages. This solution used the KEEP-ALIVE/NODE-ALIVE approach proposed in Silva et al. (2011). In this approach, the attached AP sends KEEP-ALIVE messages at periodic intervals. So, the sensor node knows the exact instant to hear for that message. If the sensor node does not receive this message, it sends a NODE_ALIVE message and waits for the return of the AP. If the return message is not received during the wait time, then the sensor node enters in scan mode to search for a new AP. This approach allows that sensor nodes become inaccessible if they do not realise in time that they are out of coverage area of the attached AP.

Garbi et al. in Bag et al. (2009) proposed an intra-mobility solution for 6LoWPAN named LoWMob. This solution comprises three main elements: a gateway, static nodes and mobile sensor nodes. Static nodes are placed in strategic localisations of the monitored area and they support a multi-hop communication from/to the gateway to/from the sensor nodes. These static nodes are resource-constrained and, therefore, they went in sleep mode at periodic intervals to conserve energy. In this proposal, these static nodes assure the intra-mobility approach. If a link quality between the sensor nodes and the static node drops below a predefined threshold, then the static node assumes that sensor node is moving out of its coverage area. At this moment, the static node must inform the adjacent static node to search for this sensor node. To determine the adjacent static node in the route of the sensor node movement direction, this proposal uses the Angle of Arrival (AoA) (Ash et al., 2005) approach. The adjacent static node now starts to search for this sensor node by sending *hello_packet*s at some intervals. When the adjacent static node detects the sensor node, it sends a message to the previous static node. This message is used to create a tunnel between the two static nodes to send the possible incoming messages to the new location. If the adjacent static node does not find the sensor node, then the previous static node wakes all the surrounding static nodes to search for the sensor node until they found it. In Jara et al. (2009, 2010a, 2010b), a similar solution to support intra-mobility of mobile sensor nodes in patients monitoring when hospitalised is proposed. This solution allows the static nodes to change into sleep mode, which may not be compatible with a continuous communication. Moreover, in this solution, adjacent static nodes must be reachable each other to allow communication. This feature implies an increased number of static nodes used for monitoring a given area.

In this paper, a new intra-mobility solution allowing continuous communication with the nodes in HWSNs is presented. This solution gathers contributions from the above-described approaches and tries to optimise the number of exchanged messages between mobile sensor nodes and the APs. It also reduces the need of multicast messages when compared with the above-described proposal. These features contribute to better energy consumption of the network elements and, therefore, increasing their lifetime. The next section describes the used method to calculate the connection probability of sensor nodes using an available propagation model.

3 Connection probability based on available propagation model

AP coverage recovery must be enough to get continuous communication. Sensor nodes use the RSSI parameter to decide to perform a handover. In this section, a relation between RSSI and distance from the AP will be established. A sensor node needs to get enough RSSI to communicate. If RSSI is low, the probability to be disconnected is decreased. By using these two facts, we can estimate the distance of the recovering area to get a high probability to be connected. The connection probability estimation of sensor nodes using the Log-Normal Shadowing Path Loss Model is described here (Rappaport, 2002).

3.1 Received Signal Strength Indicator (RSSI)

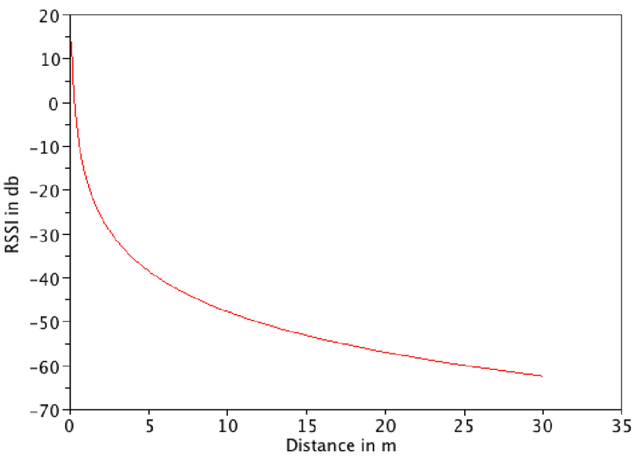
The RSSI is related to the power received by the sensor node from the base station. This power is decreasing in function of the distance for access point to the sensor node. In Molisch et al. (2004), a channel model is provided. This model proposes equation (1).

$$\mathrm{RSSI}(d) = \mathrm{RSSI}_0 + 10n\log_{10}\left(\frac{d}{d_0}\right). \tag{1}$$

In equation (1), d represents the distance from the access point to the sensor node; d_0 is the reference distance that is set to 1 m; the RSSI_0 is the value of RSSI parameter at 1 m and n represents the pathloss exponent.

By experimental experience, the value of RSSI_0 (@1 m) was set to −17 dB and according to Molisch et al. (2004) for indoor office the value of n was set to 3.07. Figure 1 shows RSSI values in function of the distance.

Figure 1 RSSI values in function of the distance applying equation (1) (see online version for colours)



3.2 Shadowing

In real world, the RSSI is not stable owing to shadowing. To model this fact, a Gaussian-distributed random variable X was added to equation (1) as presented in equation (2).

$$\mathrm{RSSI}(d) = \mathrm{RSSI}_0 + 10n\log_{10}\left(\frac{d}{d_0}\right) - X. \tag{2}$$

The Gaussian random variable X follows a probability density function given by equation (3), where the standard deviation (σ) was set to 3.9 according to Molisch et al. (2004).

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}}\exp\left(\frac{-x^2}{2\sigma^2}\right). \tag{3}$$

3.3 Connection probability

The minimal RSSI value to communicate (denoted as RSSI_{min}) is −50 dB. Using this value and the shadowing equation (2), the connection probability P is given by equation (4).

$$P(\mathrm{RSSI} \ge \mathrm{RSSI}_{min}) = \int f_{-\infty}^{\mathrm{RSSI}_{min}}(x)\,\mathrm{d}x. \tag{4}$$

The connection probability P in function of the distance d is drowning in Figure 2. Notice that the connection to the sensor node is always satisfied if the distance is smaller than 5 m, i.e., the connection probability is 100%. After that value, the probability to be connected is decreasing dramatically. For instance, for a distance of 15 m the sensor node only presents 20% of chances to be connected, and over 25 m no communication can be performed.

Using equations (1) and (4), an estimation of the connection probability in function of RSSI value can be established. Figure 3 presents this relationship.

Notice that at an RSSI value of −50 dB there is still a probability of 20% that sensor node can be connected. This is due to the shadowing. This evaluation was used to determine overlapped distance of adjacent APs' coverage areas to ensure continuous connection to the sensor nodes.

Figure 2 Connection probability in function of the distance (see online version for colours)

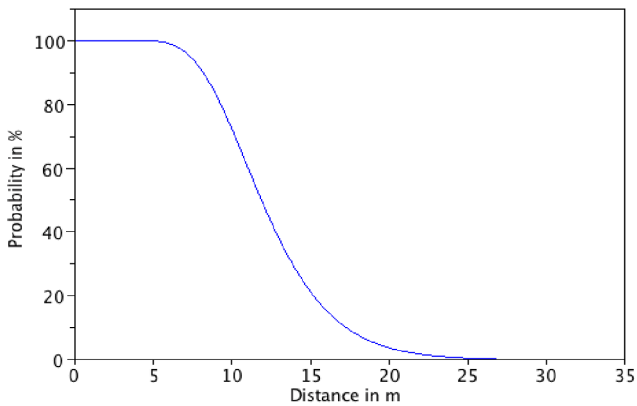
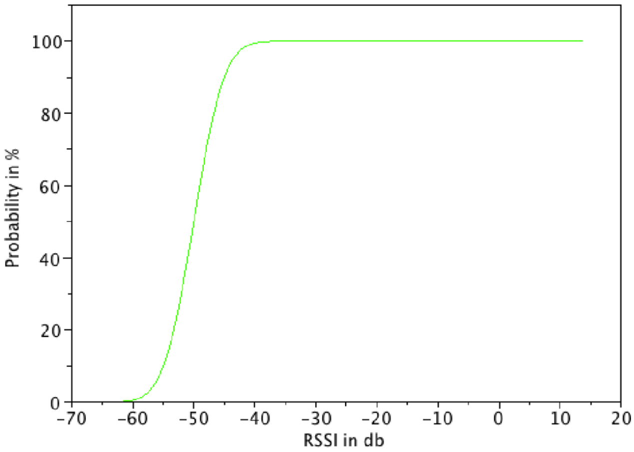


Figure 3 Relationship between the connection probability and the RSSI values (see online version for colours)



4 Intra-mobility support proposal

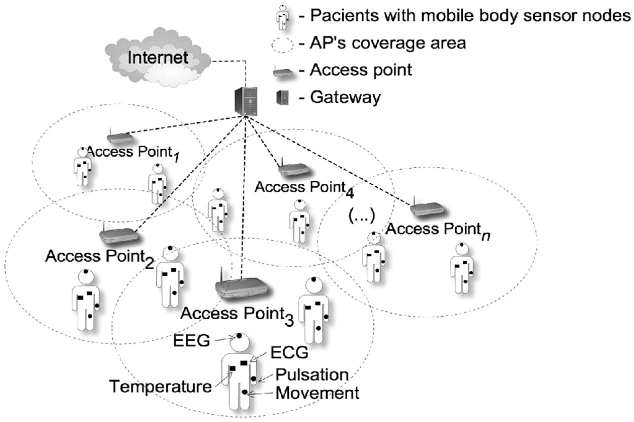
Mobility in HWSNs is important to give a better quality-of-life to the patients when hospitalised. If they can move freely around the infirmary area without concerns about the continuity of their health monitoring, it becomes a significant quality-of-life improvement. To support mobility of sensor nodes in HWSNs, the network infrastructure has to cover the entire monitored region. Because of the small coverage area of the APs when used for indoor applications (approximately 10 m (Molisch et al., 2004)), it is needed to use several APs to cover the entire area.

The main focus of this paper is the presentation of a new solution (Hand4MAC) to support intra-mobility of sensor nodes across several APs' coverage areas. This approach desires the promotion of continuous (without interruption) access to sensor nodes. Next, the network architecture of an HWSN is described.

4.1 Network architecture

The construction of an HWSN is based on the following three main elements: a gateway, APs and sensor nodes. A gateway acts as a bridge between the internet and the HWSN (a detailed description of this element is out of the scope of this paper but it can be found in Campos et al. (2011)). The APs are used as an interface to/from the sensor nodes from/to the network. The sensor nodes collect the patients' body parameters and send them wirelessly over the network. The sensor nodes can move around the monitored area always under APs' coverage area. If a sensor node moves out of APs' coverage into a new AP's coverage, it should change its network access route to maintain network accessibility. Figure 4 illustrates a generic configuration of an HWSN with the three above-described main elements.

Figure 4 Illustration of a healthcare wireless sensor network architecture



4.2 Protocol design

To ensure continuous connectivity to the mobile sensor nodes, the proposal presented in Caldeira et al. (2012a, 2013) that is based on two main assumptions was followed:

- The nodes travel across several APs' coverage areas always within the same network domain, i.e., the IP address of the sensor nodes is always the same (never changes).
- The sensor nodes tend to be always the same, i.e., it is not probable that sensor nodes are always changing, which means different IP addresses.

By the second assumption, it is possible to assume that, in a short time, all the nodes have already passed through the coverage area of all the APs in the monitored region. Therefore, if the APs save the IPs address of each sensor node that has ever been attached to them, they can then use this information to search for these sensor nodes. This process is used by the proposed solution to allow APs to search for sensor nodes that are not attached to them at the moment. This search is performed using unicast messages avoiding the use of RA messages (multicast) in the above-described proposals (in Section 2). If a sensor node is attached to an AP and it moves into an overlapped coverage area of another AP, it starts receiving search messages sent by this new AP (it is assumed that this sensor node was already attached with this new AP in the past). At this moment, the sensor node compares the RSSI of the current AP with the RSSI of the new AP and, if the new one is better than the current one the handover is performed and the sensor node passes to be attached with the new AP. To monitor the RSSI of the current AP periodically, the sensor node and the AP exchange *registration* messages. These messages are also used to renew the timestamp associated with all the attached sensor nodes. This timestamp is used by the APs to decide if the sensor node is still accessible or if it is time to start searching for it.

Each AP has two tables, *registration table* and *cache table*. The *registration table* stores the IP address and the timestamp of the last validation of all sensor nodes attached with the AP. The *cache table* stores the IP address of all the sensor nodes that have already been attached with the AP but now not. So, if a sensor node does not revalidate its timestamp in a predefined Time-to-Live (TTL) period with its attached AP, it assumes the sensor node is no longer accessible and moves the sensor node's IP address from the *registered table* to the *cache table*. Periodically, at short periods of time (1 s), each AP sends search messages (unicast) to all the sensor nodes in its *cache table*. When a node decides to handover, it sends a *disassociation* message to its current AP to inform this one that this sensor node is no longer attached with it. At this moment, the current AP moves the IP address of this sensor node from its *registered table* to its *cache table.*

When a sensor node enters for the first time into an AP coverage area, this means the AP does not know this sensor node. So, the AP is not searching for this sensor node. The sensor nodes support this situation by sending multicast messages to make themselves known by the APs. After the sensor nodes become known by all the APs in the monitored region, this process is no longer needed. The mobility support of sensor nodes and handover decisions should be assured by the search messages sent by the APs.

4.3 Network design considerations

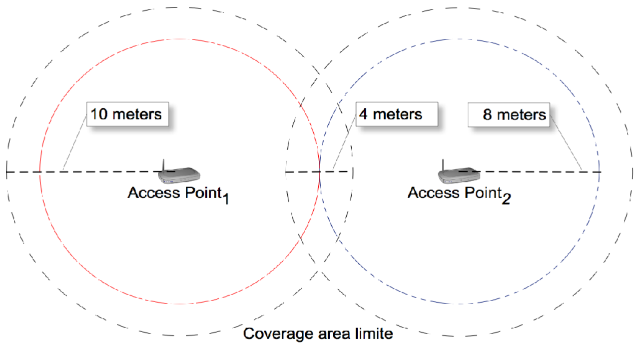
In HWSN, the continuous connection to the sensor nodes is important to keep a real-time motorisation of patients' health conditions. To ensure this behaviour, the probability of sensor nodes connection should ideally be 100%. Regarding Figure 2, the maximum distance that allows approximately a 100% probability of connection is around 6–8 m. Looking at Figure 3, in terms of decibels, the minimum RSSI value that can guarantee about 100% of connectivity to the sensor nodes is between −40 dB and −44 dB.

With this evaluation, it was possible to determine that keeping a 100% of connectivity to the sensor nodes the minimum distance for the overlapped coverage areas of two adjacent APs must be between 4 and 8 m. To minimise the number of used APs, it was considered 4 m for the overlapped coverage areas when designing the network scenarios. In Figure 5, it is presented the overlapped coverage areas of two adjacent APs used in the network design for this proposal.

5 Testbed deployment

The proposed handover solution (Hand4MAC) follows a different approach when compared with the most solutions described in Section 2 (Fotouhi et al., 2010; Zinonos and Vassilioum, 2010; Zinonos et al., 2011; Jara et al., 2011). Hand4MAC does not base its operation on continuous monitoring of the RSSI values between sensor nodes and APs. To monitor this value and announce the presence of sensor nodes, the described solutions use route advertisement (RA) messages. These messages are sent in a multicast way. The intensive usage of multicast is very penalising for the lifetime of the sensor nodes. Therefore, Hand4MAC minimises the use of such messages privileging the use of unicast messages to support the handover process. Using a laboratory testbed, this section demonstrates that Hand4MAC presents better performance in terms of optimisation of the handover process relatively to RSSI monitoring-based solutions (RSSI-based) described in Section 2. This testbed improves the previous proposal presented in Caldeira et al. (2012b).

Figure 5 Illustration of the overlapped coverage areas of two adjacent APs (see online version for colours)



5.1 Testbed construction

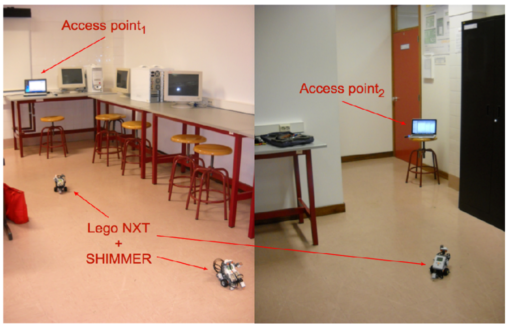
To evaluate the Hand4MAC proposal, a laboratory prototype was developed. This prototype follows the configuration of the scenario presented in Figure 4. For this deployment, it was used two APs. In terms of hardware, each AP includes a receiver/sender interface attached to a computer using Universal Serial Bus (USB) connection. The positioning of each AP in the testbed takes into account the assumptions described in Subsection 4.3. Six sensor nodes travel between the coverage areas of the two APs with a velocity of approximately 2 m per second (the velocity of a person walking). The sensor nodes hardware used for this experiment was the Sensing Health with Intelligence Modularity, Mobility and Experimental Reusability (SHIMMER) platform. For the APs' receiver/sender interface, it was used a TelosB platform. The sensor nodes were running the appropriated developed firmware to operate as described in Section 4. This firmware was developed in TinyOS 2.1.1 with nesC programming language. The APs' receiver/sender interfaces were running the IPBaseStation example available in TinyOS and operating in IEEE 802.15.4 channel 15. The devices running this firmware must be connected to a computer through a USB connection. This firmware only forwards messages that arrive on this device wirelessly to the attached computer via USB and *vice versa*.

Figure 6 presents the laboratory testbed scenario used on these experiments. To simulate the patients moving around the coverage area, three Lego NXT platforms were used.

These robots were programmed to move in a random way at a constant speed of 2 m per second within the coverage area of the two APs. Each Lego NXT carries two SHIMMER sensor nodes.

To manage the handover process in the APs' side, a software module running in the AP's computers was developed. This module named as Mobility Support Module (MSM) was developed using Java programming language and works as follows. The MSM is composed of three threads and two tables. The *Main* thread accepts all the requests for registrations by the sensor nodes that came into the AP's coverage area. If a sensor node was never registered to this AP, a new entry in *IPArray* table is created. The *HistIP* thread is always trying to contact old registered sensor nodes presented at the *HistIPArray* table. If it is possible to contact one of the old sensor nodes and if the sensor node decides to register with this AP, then *HistIP* thread moves the sensor node's entry from *HistIPArray* to *IPArray*. The *IPArray* table hosts the information of AP's registered sensor nodes. This information is sent to the gateway whenever there is a change. Thus, the gateway always knows which AP could reach each sensor node. Some sensor nodes could move out of the AP's coverage area and fail the un-registration procedure. Thus, *CleanIPArray* thread periodically searches *IPArray* table for expired TTL registrations. If found, the entries are moved from this table to *HistIPArray* table. The MSM was running over the Ubuntu 10.0.4 operating system installed in the computers. In Figure 7, it is presented an overview of the software components developed to support intra-mobility of sensor nodes. Figure 8 presents the architecture of the MSM and the relation between all the elements that belong to this module.

Figure 6 Laboratory testbed used for the experiments, composed by two APs and three Lego NXT robots carrying each one two SHIMMER sensor nodes (see online version for colours)



To evaluate the accessibility of the sensor nodes by the network, an additional tool was developed. This tool was running on each AP's computer. It always monitors the connection to the entire sensor nodes registered with this AP. This tool sends (every half second) a unicast message to each registered sensor node and waits for its reply. If the sensor node does not reply, it is considered that this sensor node is no longer accessible. Both the MSM and the connection tool register on a graphical interface the information of their operation. The MSM interface shows information about all the events related to the handover process. The connection tool interface shows information about the sensor nodes that have been reached. Figure 9 presents two screenshots of the developed tools to support intra-mobility of sensor nodes in the testbed. The screenshots present an output example from performed experiments.

Figure 7 Illustration of network architecture regarding developed software components

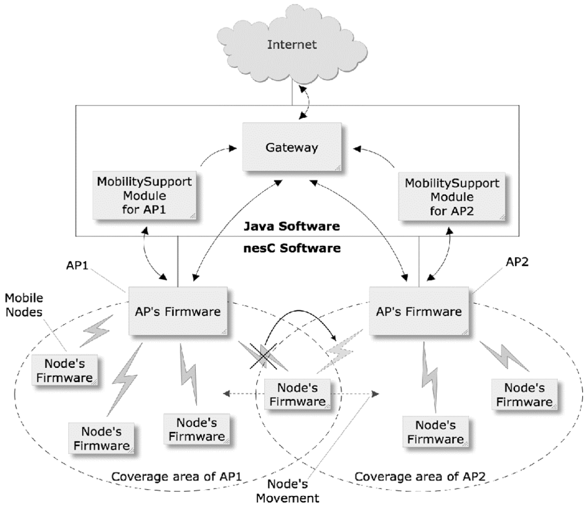


Figure 8 Mobility Support Module architecture

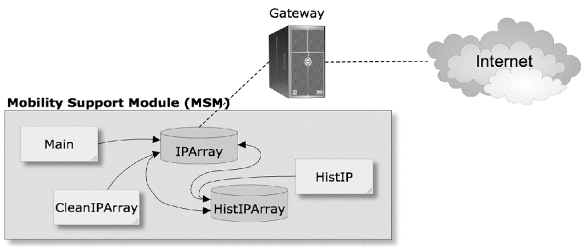
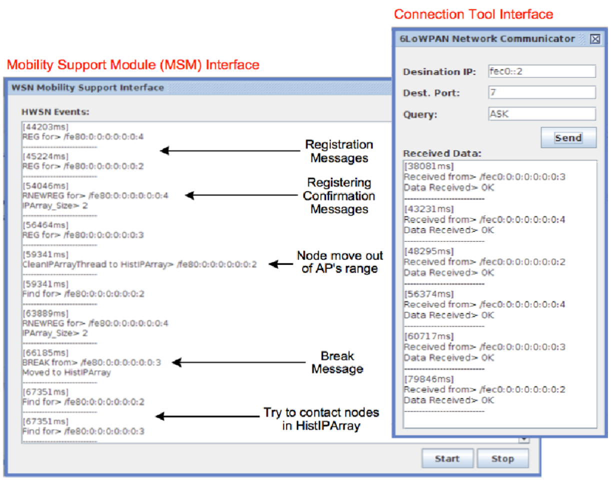


Figure 9 Screenshot of developed tools to support the mobility of sensor nodes in the testbed (see online version for colours)



6 Performance assessment

This section focuses on the performance evaluation of the Hand4MAC proposal using the above-described testbed (scenario). To evaluate this proposal, each experiment took about 30 min. During this time interval, the sensor nodes travel around the coverage area of the APs with a constant speed of 2 m per second. It was collected the information about the connectivity (using the connection tool) to all the six sensor nodes used in this experiment. With the data collected, it was possible to determine the percentage of time that each sensor node was reachable by the network (i.e., registered with an AP).

These values were compared with the ones obtained in the same network scenario conditions by the use of an RSSI-based solution. This solution follows the principles (described in Section 2) used by Fotouhi et al. (2010), Zinonos and Vassilioum (2010), Zinonos et al. (2011) and Jara et al. (2011) to monitor the connectivity to the sensor nodes. The RSSI-based solution works as follows: at periodic time intervals, sensor nodes send probe messages to their current APs. Then, APs acknowledge that messages and sensor nodes evaluate whether the RSSI value is below a predefined threshold. If yes, the sensor nodes start a handover process.

Figure 10 presents the percentage of time that each sensor node remains accessible by the network, on average, over 30 min when using the two handover approaches. Using the Hand4MAC approach, the sensor nodes remain connected to the network about 97.8% of the time, on average, whereas when using the RSSI-based solution this value is only about 93.5%, on average.

Figure 10 Time percentage that each sensor node remains accessible by the network using both the Hand4MAC and the RSSI-based handover solutions

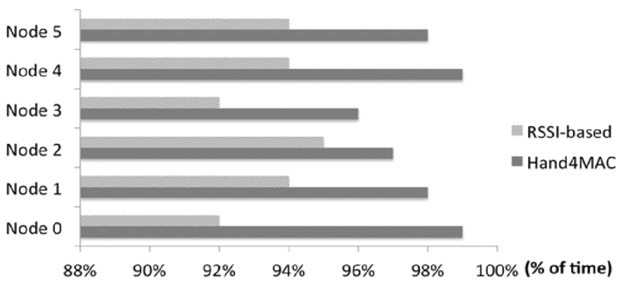


Table 1 shows the number of messages exchanged between sensor nodes and APs to support the two handover mechanisms. These values demonstrate that the Hand4MAC solution uses less than 37.6% of sent messages, on average, when compared with the RSSI-based solution. Concerning to received messages, the Hand4MAC uses less than 1.9%, on average. Relative to multicast messages, the Hand4MAC uses less than 98.5%, on average, than the other solution.

Figure 11 represents the connection activity of a sensor node during about 300 s of the experiment. In this representation, it is possible to view the sensor node changes its registration between the two APs. It is also possible to verify the time of disconnection was almost negligible. The total time of 300 s this sensor node stays disconnected was about 13 s, i.e., 4.3% of the total time. This means the sensor node remains accessible 95.6% of the time. Also, when the sensor node becomes disconnected, it remains in this situation for only about 2.16 s, on average. Then, it can be concluded that Hand4MAC can ensure almost continuous connection to the sensor nodes in the HWSN with a small amount of exchanged message. Also, a valuable point of this solution is the use of very few multicast messages.

Table 1 Number of exchanged messages (sent, received and multicast) between sensor nodes and APs when using both Hand4MAC and RSSI-based handover solutions

	Sent		*Received*		*Multicast*	
	Hand4MAC	*RSSI-based*	*Hand4MAC*	*RSSI-based*	*Hand4MAC*	*RSSI-based*
Node 0	410	662	616	632	4	335
Node 1	441	673	730	648	6	341
Node 2	412	686	611	670	5	345
Node 3	428	666	598	638	7	337
Node 4	414	680	659	659	2	344
Node 5	417	676	612	655	6	340
Average	*420.3*	*673.8*	*637.7*	*650.3*	*5*	*340.3*

The TTL parameter can influence the performance of the connectivity of the sensor nodes with the network. Next, the results obtained when using different TTL values for Hand4MAC and RSSI-based approaches are discussed. The TTL parameter in RSSI-based solution represents the time interval between probe messages sent by the sensor nodes to their current APs. In Hand4MAC, this parameter is used as time interval between sensor nodes' register revalidation. All the above-presented results used a TTL of 5 s. Another study with three different values of TTL is also addressed. For the first experiment, it was used a TTL value of 10 s. In Figure 12 are presented the connection percentage for the two approaches in those conditions.

Figure 13 presents the percentage of time that each one of the 6 sensor nodes in the scenario remains connected to an AP using a TTL of 30 s. Regarding these results, it is possible to determine that Hand4MAC guarantee a connection of 77% (on average) whereas RSSI-based only guarantee 67%.

If a TTL of 60 s is used, the percentage of time connection drops for 66% using Hand4MAC and 56% using RSSI-based. This result can be observed in Figure 14.

Regarding these results, it can be concluded that Hand4MAC improves the connectivity of sensor nodes and APs when compared with the RSSI-based approach. For different values of TTL (5, 10, 30 and 60 s), Hand4MAC guarantees approximately more than 10% of connectivity, on average.

Figure 11 Connection activity of a sensor node when travels across AP1 and AP2 coverage areas during 300 s (see online version for colours)

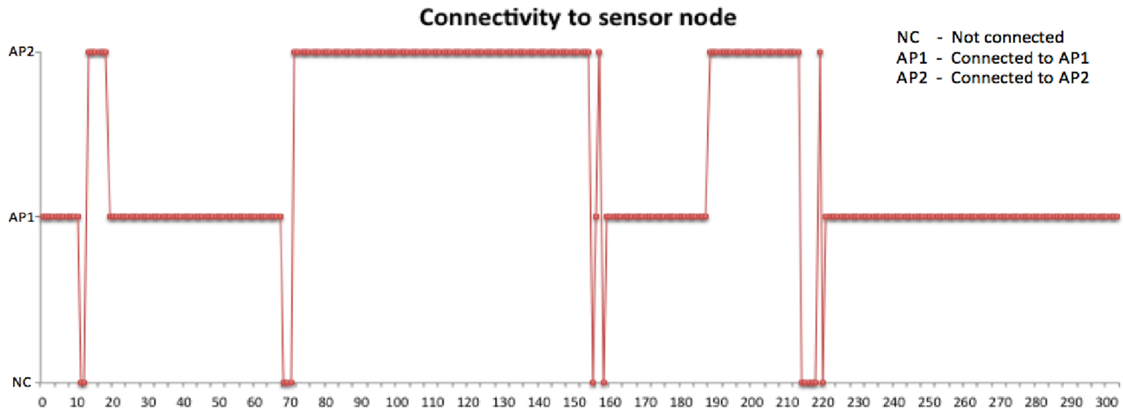


Figure 12 Time percentage that each sensor node remains accessible by the network using both Hand4MAC and RSSI-based handover solutions with TTL = 10 s (see online version for colours)

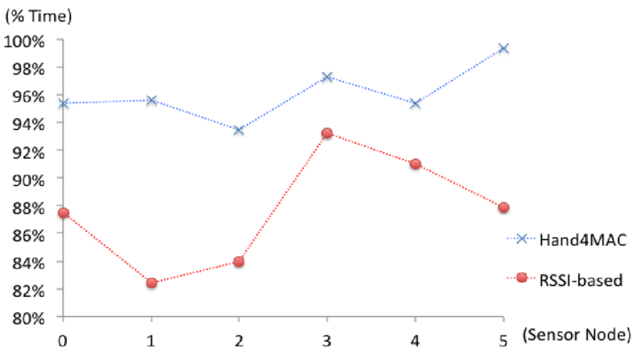
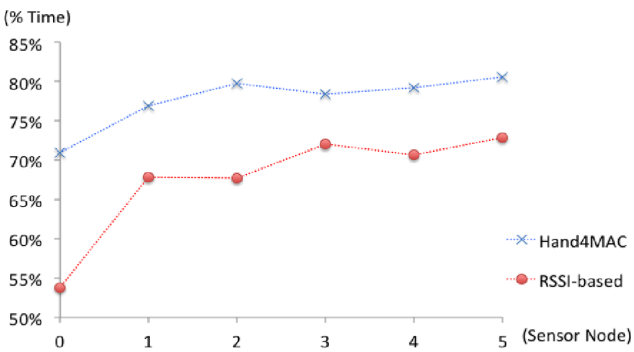


Figure 13 Time percentage that each sensor node remains accessible by the network using both Hand4MAC and RSSI-based handover solutions with TTL = 30 s (see online version for colours)

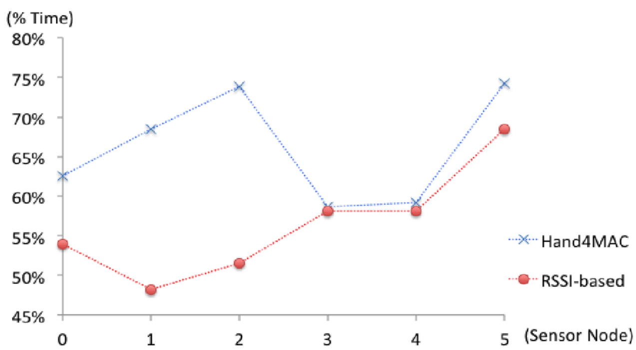


7 Conclusion

Keeping the hospitalised patients always under monitoring is a difficult task when applying the traditional ways. Using HWSNs can be an asset to promote a close control and monitoring of health parameters of the patients. These solutions should support a continuous and real-time access to the sensor nodes attached to the patients. Moreover, taking into account the quality-of-life of the patients when hospitalised, it is important to let them move around if they can. Keeping the sensor nodes always accessible while in moving is not easy. This feature becomes a new challenge to the HWSNs. To cover the entire area of an infirmary or even of a hospital with wireless network access, it is needed the use of several access points. To remain the sensor nodes always accessible when travelling through several APs' coverage areas, they must change their points of attachment to the network. Several solutions are proposed to optimise this situation. This paper presented a handover support solution for HWSNs. This solution was evaluated in a laboratory testbed and it was compared with an RSSI-based proposal. The results demonstrated that the proposed solution (Hand4MAC) is more efficient than the other solution. The Hand4MAC allows almost continuous communication to the sensor nodes all the time with much less exchanged messages than the most used solution (RSSI-based).

The next steps will try to optimise this solution even more in terms of messages exchanged between the sensor nodes and the APs. Furthermore, the construction of a user-friendly interface to access the data collected by the sensor nodes and represent the localisation of the patients in the monitored area is part of the future work.

Figure 14 Time percentage that each sensor node remains accessible by the network using both Hand4MAC and RSSI-based handover solutions with TTL = 60 s (see online version for colours)



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Chapter 8

Conclusion and Future Work

This chapter addresses the main conclusions of the research work presented in this thesis. Furthermore, at the end of this chapter some future research directions are proposed.

1 Final Conclusions

This thesis proposes a new healthcare wireless sensor network (HWSN) handover mechanism that supports continuous and real-time access to the sensor nodes with small amounts of energy expenditure. To achieve this objective the research work was divided in four main parts. These parts can be summarized as follows: the first part was dedicated to the study of the research topic and analyses of the state of the art in order to identify the main open issues; second part was dedicated to an in depth understanding of the limitations of sensor nodes and the need to optimize their operations; third part describes the proposal of a new handover mechanism that supports continuous connection to the sensor nodes with optimized energy expenditures; the final part was devoted to the performance assessment of the proposed handover mechanism using both, simulation tools and a real testbed.

The first part of this research work was included in chapters 1 and 2 of this document. At this stage a detailed investigation of the topic of this thesis was performed in order to clearly understand the state of the art. Then, the focus of this research work was defined and delimited and its main objectives were described. In chapter 1 the main contributions that result from this work and that integrate this document were also presented. Chapter 2 presents a comprehensive survey on the subject under appreciation, reviewing the main existing solutions for handover in wireless sensor network (WSN) and considering their applications in HWSNs. After analysing and identifying the main limitations of the existing solutions, some open issues are identified and discussed.

The main objective of this research work is to propose a new handover mechanism that guarantees continuous access to mobile sensor nodes in HWSNs with reduced amounts of energy expenditure. The solutions already proposed in the literature are not yet satisfactory for continuous connection to mobile sensor nodes. These solutions were design for sparse and on demand access to sensor nodes and therefore do not need continuous connectivity. In health scenarios the control over patients' state needs to be very tight and therefore continuous access to sensor nodes is essential. Due to the access points' (APs) wireless coverage limitations (about 10 meters for indoor applications) several of these must be used to cover, for example, an entire area of a hospital ward. Sensor nodes can move across different APs' coverage areas and the big problem is to manage the link transitions between APs in order to guarantee continuous connection to the sensor nodes. None of the solutions is able to be aware of exact moment to perform a link transition (handover) and, if this transition is beneficial or not for the future trajectory of the sensor node. Therefore, these decisions have to be performed using the actual information collected by the network elements (APs and sensor nodes). Most of the handover solutions base their operations in link quality metrics evaluation. Until now, these kinds of metrics proved to be the best way to decide to perform a handover or not. This metrics represents the signal power used to transmit a message from the sender to the receiver. They are easily obtained by the network operation itself and additional hardware to collect them is unnecessary. Other existing handover proposals use additional hardware to collect other information (e.g. global positioning system (GPS), radio frequency, infrared, …) but the use of this hardware increases the power consumption of the sensor nodes and therefore reduces their lifetime. The sensor nodes used in HWSNs are tiny devices powered by batteries with small capacities. Thus, reducing their energy expenditure is vital to keep them operating.

The metrics used for link quality evaluation is typically one of either received signal strength indicator (RSSI) or link quality indicator LQI. The values of these metrics are ideally proportional to the distance between sender and receiver. To collect the information about this metric a message should be exchanged between sender and receiver. Most of the handover solutions proposed in the literature periodically exchange messages between sensor nodes and APs to evaluate the quality of the link. The number of messages exchanged significantly influences the energy consumption of the sensor nodes. Thus, this research work proposes a new approach that supresses the need for continuous monitoring of the link quality value.

The second part of this research work, presented in chapter 3, was dedicated to understanding the hardware limitations of a sensor node. To accomplish this partial objective, a new biosensor platform was developed to collect intra-vaginal temperature. The construction of this new biosensor allowed for necessary knowledge to be obtained for an in depth understanding of all the limitations of a sensor node. This knowledge was crucial for the proposal of a handover mechanism that could be energetically optimized.

The third part of this research work was described in chapters 4 and 5. In this part a new handover mechanism was proposed to support the continuous connection to mobile sensor nodes in a HWSN. The proposed mechanism, denoted as handover for MAC layer (Hand4MAC), uses a cache memory in the APs side to store the information about all the sensor nodes that were already registered with them. This information is then used to try to contact the sensor nodes later again. When a sensor node moves out of an AP coverage area and then it returns, it will start receiving messages from this AP. These messages are unicast and when the sensor node receives one of these messages it decides to handover or not. The decision is performed by the evaluation of the registered AP's RSSI value, and the RSSI value of the message received from the new AP. The best value wins. Unlike the most common handover mechanisms used in WSNs (now on denoted as RSSI-based mechanism), the Hand4MAC avoids the need for continuous exchange messages to evaluate the link quality between sensor nodes and APs. The Hand4MAC also supresses the intensive use of multicast messages by the APs to search for new sensor nodes within their coverage area. The validation of this mechanism was demonstrated by several experiments. These experiments confirmed that Hand4MAC could guarantee almost continuous connection to the sensor nodes with less energy expenditure when compared to the RSSI-based mechanism. The experiments considered two different situations. In the first the time-to-live (TTL) value was the same for both mechanisms. The results demonstrated that Hand4MAC reaches 98% of connection to the sensor nodes while the RSSI-based mechanism only reaches 87%. In terms of messages exchanged Hand4MAC has used almost the same number of received messages, 29% less in sent messages, and 94% less in multicast messages than the RSSI-based mechanism. In the second situation, the TTL value for the RSSI-based mechanism was increased in order to achieve better connectivity with the sensor nodes. In this case, using the RSSI-based mechanism, the connection percentage with the sensor nodes increased to almost 98%. However the number of exchanged messages also increased significantly. Compared with Hand4MAC, the RSSI-based mechanism received 535% more messages, sent 735% more messages, and has used 1840% more multicast messages. As it could be easily concluded that for RSSI-based mechanism, when the TTL value is reduced, the time period that sensor nodes remain connected to the network increases. However, the number of exchanged messages also increased. As a result, the lifetime of the sensor nodes' batteries was strongly reduced.

The fourth part of this research work includes chapters 6 and 7. This part was dedicated to the performance assessment of the Hand4MAC mechanism, in comparison with the other handover approaches presented in the literature. The performance assessment of Hand4MAC took place in two different scenarios, one using simulation tools and other with a real testbed. With the simulation tool OMNeT++ several experiments were performed using a hospital ward simulation scenario. These experiments proved that Hand4MAC could guarantee almost continuous connection to the sensor nodes with less energy consumption in comparison with other trivial solutions. It was also demonstrated that Hand4MAC was flexible enough to be applied in situations where the sensor nodes needed to travel at higher velocities and where the density of the sensor nodes increases. The results demonstrated that independently the number of sensor nodes in the scenario traveling at velocities between 2m/s to 5m/s the Hand4MAC mechanism could guarantee over 90% connection to sensor nodes. The results have also proven that the Hand4MAC mechanism could reach that percentage of connection with less energy consumption in comparison with other handover solutions.

Afterwards, the Hand4MAC mechanism was validated in a real laboratory testbed. The testbed was constructed with six commercial sensor nodes platforms (SHIMMER), two access points, and three mobile robots (Lego NXT) to simulate the patients moving around. The evaluation was focused on the percentage of time that sensor nodes remained accessible to the network and the number of messages used by the handover mechanism. The influence of the TTL value in the connectivity of the sensor nodes to the network was also studied. The results obtained demonstrated that, with a TTL of 5 seconds the Hand4MAC mechanism could reach about 98% connection to the sensor nodes with 38% less sent messages, less than 1.9% of received messages, and less than 98.5% of multicast messages, in comparison to other handover solutions. The other values of TTL under appreciation were 10 seconds, 30 seconds, and 60 seconds. The results proved that the Hand4MAC mechanism could guarantee 10% more connectivity to the sensor nodes than the most common handover solutions.

The main objective of this thesis was accomplished by the presentation of a new handover mechanism (Hand4MAC) to support continuous and real-time access to mobile sensor nodes in HWSNs with small amount of energy expenditures. This objective was carried out taking into account the sensor nodes hardware construction, the software optimization, and the control of messages exchanged. Furthermore, as a result of this research work it was also possible to demonstrate the flexibility of the Hand4MAC for application in scenarios that need faster sensor nodes with similar results. The contributions of this research work are likely to be of relevance in the field of the wireless sensor networks in general and to the healthcare wireless sensor networks in particular.

As a final remark, it is important to note that this research work is part of the national project AAL4ALL (Ambient Assisted Living for All), co-funded by COMPETE under FEDER via QREN Programme. The main objective of the AAL4ALL project is the development of an ecosystem of products and services for Ambient Assisted Living (AAL) associated to a business model and validated through large scale trial. This research work constitutes with a great effort to accomplish the main objective of the AAL4ALL project.

2 Future Work

To conclude this thesis, the next paragraphs present some future research directions that can be followed and which result from this research work.

When a new sensor node, which enters for the first time in a network, becomes known by one of the APs, it could be interesting to let the other APs receive the information about that sensor node too. The development of these mechanisms could be part of future enhancements of the Hand4MAC mechanism. This feature could eliminate the need to use multicast messages when the sensor node enters a coverage area of an AP that does not know it. This feature could further increase the connectivity of the sensor nodes to the network and reduce the multicast message usage.

The deployment of the Hand4MAC mechanism in a real scenario, like a real hospital ward, becomes part of the future work of this investigation. This task is already on going with its inclusion on the AAL4ALL project.

To visualize the information collected by the sensor nodes and their location in a real scenario the development of a user-friendly interface should be performed in the future. This interface should allow real-time access to the data collected by the sensor nodes and remote configurations. Also, this application should include an autonomous operation that could detect some abnormal values in patients' health parameters and trigger a system of local (in the building) alerts, or if needed remote (out of the building) alerts. This system could include all kind of networks, like Wi-Fi, global system for mobile communications (GSM), Ethernet, Bluetooth, etc.

In terms of hardware development the inclusion of power scavenging technics in the sensor node construction could help to increase their batteries' lifetime. Also, the reduction of the size of sensor nodes' hardware components could contribute to the construction of small sensor nodes and therefore more comfortable for patients to carry.