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AN EFFICIENT NETWORK MOBILITY MANAGEMENT FOR A 6LoWPAN MOBILE NETWORK IN HOSPITAL ENVIRONMENTS

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By

MOHAMMADREZA SAHEBI SHAHAMABADI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia In Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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October 2017

Chairman: Professor Borhanuddin b. Mohd Ali, PhD
Faculty: Engineering

In recent times, the hospital wireless sensor network (HWSN) has become one of the most important IPv6 over low-power personal area network (6LoWPAN) applications because the patients are attached with tiny 6LoWPAN sensors. One of the application scenarios is the monitoring of patients' vital signals while the patients are on the move within the hospital premise. Among the different WSN mobility protocols, NEMO is the most common for 6LoWPAN mobile network in buildings equipped with wireless network infrastructure, such as with the case at modern hospitals and clinics. Current network mobility solutions do not perform well in terms of end-to-end delay, packet loss, handover signalling delay and signalling cost in 6LoWPAN area, to keep continuous connectivity for transmitting patients' vital signals. To this date, only a few works on NEMO for 6LoWPAN mobile networks have been reported. The foremost demand of medical application is the need to ensure quality of service (QoS) for data transfer due to its criticalness in medical context. This thesis aims to present an efficient mobility management protocol for HWSNs to reduce patient's data packet loss rate, signalling cost, handover delay, end-to-end delay, and optimize the energy consumption to maintain continued connectivity with the remote care giver.

The effects of three design parameters, namely number of mobile network nodes (MNNs), number of handovers, and MNN packet generation rate in NEMO are evaluated. It is shown that the mobile router (MR) suffers from high energy consumption and traffic congestion which result in a bottleneck. If the MR drains its energy entirely, the connectivity with home network will be lost. Hence, in this thesis, we propose a number of schemes for NEMO based on 6LoWPAN MNNs. The first scheme improves the NEMO handover process on HWSN based on 6LoWPAN called HWSN6 mobility solution. This is extended to MR to offer a fast handover mechanism with low handover

signalling cost, handover delay and packet loss, respectively. The second scheme is a message-scheduling algorithm based on route optimization in tunnelling process between the MNNs and HA to decrease the traffic congestion at MR and packet end-to-end delay. The third scheme considers on the remaining energy of MR to optimize energy consumption to prolong the connectivity between MNNs and HA, this is called selective optimal MR algorithm.

The results are drawn from analytical models and OMNeT++ simulator running on Contiki to perform the 6LoWPAN adaptation layer tasks. An analytical model of the proposed scheme is derived for handover signalling cost, handover signalling delay, and tunnelling cost. Simulation results show that the proposed solution reduces traffic congestion at MR by using the HWSN6 handover solution and the message-scheduling algorithm in the tunnelling process. The number of handover signalling messages is reduced from 6 stages in MIPv6 to 3 stages, this is achieved by exploiting other network elements such as border router (BR). The handover signalling costs and packet loss in the proposed scheme, NEMO-HWSN, are optimized around 13% and 31% respectively and compared to NEMO. Then, by using the proposed message-scheduling algorithm, end-to-end delay in NEMO-HWSN is reduced by approximately 20%. Finally, by using the selective optimal algorithm, the MR energy consumption in NEMO-HWSN is minimized by approximately 15.5%. Our proposed scheme also has a good performance for intra-PAN mobility like hospital environments because it skips the “Binding” and “Challenge” process in intra-PAN mobility. The above results proved that the NEMO-HWSN is more efficient than other schemes in the HWSN environment, with low handover signalling delay, handover signalling cost, packet loss, packet end-to-end delay and energy consumption. Analytical models and simulation have been conducted to show the validation of work to verify that simulation results correspond to reference values (MIPv6, NEMO and HWSN6).

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

PENGURUSAN MOBILITI RANGKAIAN BAGI RANGKAIAN MUDAH ALIH 6LoWPAN DALAM PERSEKITARAN HOSPITAL

Oleh

MOHAMMADREZA SAHEBI SHAHAMABADI

Oktober 2017

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Pada masa mutakhir ini, rangkaian penderia tanpa wayar di hospital (HWSN), yang mana pesakit adalah diliputi dengan penderia IPv6 di atas rangkaian kawasan peribadi bertenaga-rendah (6LoWPAN), telah menjadi salah satu dari aplikasi terpenting 6LoWPAN. Salah satu dari senario aplikasinya adalah bagi pemantauan isyarat penting dari pesakit apabila pesakit sedang bergerak dalam kawasan hospital. Di antara beberapa banyak protokol mobiliti WSN, NEMO adalah paling lazim digunakan untuk rangkaian bergerak 6LoWPAN dalam bangunan yang dilengkapi dengan prasarana rangkaian tanpa wayar, seperti yang terdapat dalam hospital dan klinik yang modern. Penyelesaian bagi mobiliti rangkaian masa kini tidak menunjukkan prestasi yang baik dari segi lengah hujung-ke-hujung, kehilangan paket, kelewatan isyarat penyerahan dan kos pengisyaratan apabila digunakan bersama 6LoWPAN. Sehingga kini, hanya beberapa kajian tentang NEMO bagi rangkaian mudah alih 6LoWPAN telah dilaporkan. Permintaan yang paling utama untuk aplikasi perubatan adalah untuk mempastikan kualiti (QoS) untuk penghantaran data oleh kerana runcingnya keadaannya dalam konteks perubatan. Tesis ini membentangkan satu protokol pengurusan mobiliti untuk HWSN untuk mengurangkan kadar kehilangan paket data, lengah penyerahan dan hujung-ke-hujung masing-masing, dan mengoptimumkan penggunaan tenaga untuk mengekalkan penyambungan kepada pemberi penjagaan yang berada pada jarak jauh.

Kesan kepada tiga parameter reka bentuk, iaitu bilangan nod rangkaian bergerak (MNNs), bilangan penyerahan dan kadar penjanaan paket dari MNNs, masing-masing, telah diniliai. Adalah ditunjukkan bahawa penghala mudah alih (MR) mengalami penggunaan tenaga yang tinggi dan kesesakan trafik yang mengakibatkan keadaan terjerut. Jika tenaga MR hapus keseluruhannya, sambungan antara rangkaian mudah alih dengan rangkaian perumah akan hilang. Oleh itu, di dalam tesis ini, kami mencadangkan beberapa skim untuk NEMO berdasarkan MNN 6LoWPAN. Skim yang pertama memperbaiki proses penyerahan NEMO ke atas HWSN berasaskan 6LoWPAN yang dipanggil sebagai penyelesaian mobiliti HWSN6. Ianya dilanjutkan pada MR untuk menyediakan mekanisma penyerahan yang lebih pantas beserta kos pengisyaratan yang rendah. Skim yang kedua ialah algoritma penjadualan risalah berasaskan pengoptimuman laluan dalam proses penorowangan di antara MNNs dan HA, bagi mengurangkan kesesakan trafik pada MR dan lengah hujung-ke-hujung. Skim yang ketiga mempertimbangkan baki tenaga MR untuk mengoptimumkan penggunaan tenaga rangkaian mudah alih untuk memanjangkan tempoh penyambungan antara MNN dan HA, ini dipanggil sebagai algoritma MR optimum terpilih.

Hasil keputusan adalah dipetik dari model analitik dan simulator OMNet++ yang beroperasi di atas Contiki untuk melaksanakan tugasan lapisan adaptasi. Satu model analitik pada skim cadangan ini adalah diterbitkan untuk mendapatkan kos pengisyaratan penyerahan, lengah pengisyaratan penyerahan, dan kos penerowongan. Hasil keputusan simulasi menunjukkan bahawa penyelesaian cadangan ini dapat meringankan kesesakan trafik di MR dengan menggunakan penyelesaian penyerahan HWSN6 dan algoritma penjadualan-risalah dalam proses penerowongan. Bilangan risalah pengisyaratan dapat dikurangkan dari 6 peringkat dalam MIPv6 kepada 3 peringkat, ini dapat dicapai dengan mengeksploitasi unsur-unsur lain rangkaian seperti penghala sempadanan (BR).Kos pengisyaratan penyerahan dan kehilangan paket dalam skim cadangan NEMO-HWSN ini, telah dioptimumkan berbanding NEMO dengan kadar 13% and 31%, masing-masing. Kemudian, dengan menggunakan algoritma penjadualan-risalah cadangan ini, lengah hujung-ke-hujung dalam NEMO-HWSN adalah dikurangkan dengan 20%. Akhir sekali, dengan menggunakan algoritma optimum terpilih, penggunaan tenaga MR dalam NEMO-HWSN dapat dikurangkan dengan 15.5% lebihkurang. Skim cadangan kami juga mempunyai prestasi yang baik untuk mobiliti intra-PAN seperti pada persekitaran hospital kerana ia tidak perlu menjalankan proses "Binding" dan "Challenge" dalam mobiliti intra-PAN. Hasil keputusan di atas membuktikan bahawa NEMO-HWSN adalah lebih cekap dari skim-skim lain dalam persekitaran HWSN, dengan pengurangan dalam lengah pengisyaratan penyerahan, kos pengisyaratan penyerahan, kehilangan paket, lengah hujung-ke-hujung dan penggunaan tenaga, masing-masing. Model analisis dan simulasi telah dilakukan untuk menunjukkan validasi kerja ini untuk mengesahkan bahawa hasil keputusan simulasi adalah sepadan dengan nilai rujukan (MIPv6, NEMO and HWSN6).

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"In the name of Allah, Most gracious, Most merciful"

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

IoT	Internet of Things
IPv6	Internet Protocol version 6
6LoWPAN	IPv6 over Low-power Personal Area Network
IETF	Internet Engineering Task Force
IP	Internet Protocol
MN	Mobile Node
PAN	Personal Area Network
MIPv6	Mobile IPv6
WSN	Wireless Sensor Network
LoWPAN	Low-power Personal Area Network
SNs	Sensor Nodes
NEMO	Network Mobility
MR	Mobile Router
MNNs	Mobile Network Nodes
MINT	Mobile Internet Router
HA	Home Agent
HWSN	Hospital Wireless Sensor Network
HWSN6	Hospital Wireless Sensor Networks based on 6LoWPAN
BR	Border Router
FA	Foreign Agent
CN	Corresponding Node
FFDs	Full-Function Devices
BU	Binding Update
DAC	Digital-Analog Converter
ADC	Analog-Digital Converter
AP	Access Point
RFD	Reduced-Function Device
MTU	Maximum Transmission Unit
MAC	Media Access Control
CFD	Coordinator-Function Device
BER	Bit-Error Rate
RSSI	Received Signal Strength Indicator
FMIPv6	Fast Mobile IPv6

HMIPv6	Hierarchical Mobile IPv6
DAD	Duplicate Address Detection
GW	Gateway
MNP	Mobile Network Prefixes
CoA	Care of Address
Home Address	HoA
AR	Access Router
VL	Visitor List
MBT	Mobility Binding Table
LU	Location Update
NP	Network Prefix
ECG	Electrocardiogram
HIS	Hospital Information System
PL-PMIPv6	Packet Lossless Proxy MIPv6
PMIPv6	Proxy mobile IP6
MAP	Mobility Anchor Point
MAG	Mobility Access Gateway
AoA	Angle of Arrival
DLowMob	Distributed LowMoB
MSPs	Mobility Support Points
SPMIPv6	Sensor proxy mobile IPv6
LMA	Local Mobility Anchors
RS	Router Solicitation
RA	Router Advertisement
WBANs	Wireless Body Area Networks
PDA	Personal Digital Assistant
AReq	Associate Request
ARep	Associate Request
RReq	Reassociate Request
RRep	Reassociate Request
NL	Node Left
Ack	Acknowledgment
BReq	Binding Request
BCh	Binding Challenge
BC	Binding Confirm
ChReq	Challenge Request

ChRep	Challenge Reply
ChF	Challenge Forward
BAN	Body Area Networks

CHAPTER 1

INTRODUCTION

1.1 Research Background

The Internet of Things (IoT) has emerged as a new paradigm for virtual things related to Internet connectivity and has caught researchers' attention in recent years Ashton, K. (2009). It is the fact that IoT varies, especially it could be used as a part of the future Internet where there are identities between physical and virtual "things". Arising from the emergence of IoT, Internet protocol version 6 (IPv6) over low-power personal area networks (6LoWPANs), which hitherto has not received a great deal of attention, has recently seen a resurgent of activities in the internet engineering task force (IETF) group (Devarapalli *et al.,* 2005). 6LoWPANs has been defined to enable IPv6 connectivity over the IEEE 802.15.4 for communications with the Internet. It leads to a global connectivity among a large number of tiny IPv6 intelligent devices over large areas, using its large address space. 6LoWPAN nodes are characterized by their low bandwidth, short range, ease of deployment, scarce memory capacity, low power consumption, limited processing capability and other attributes associated with inexpensive hardware. 6LoWPANs also has the disadvantage of limited battery capacity for devices and communication (Oliveira *et al.,* 2011 and Airehrour *et al.,* 2016).

It has been argued that mobility support is one of the most important aspects that need to be addressed for the success of IoT (Gershenfeld *et al.,* 2004 and Montavont *et al.,* 2014). This is because, many of the IoT objects are likely to be mobile and therefore require a mobility management protocol for maintaining internet protocol (IP) mobility. When a 6LoWPAN mobile node (MN) as a part of IoT moves freely, it is important to establish a system of mobility management to maintain continuous network connectivity for information to be exchanged unimpeded with the corresponding node or a server. Current mobility protocols have been constrained by limited energy and power reserves in MNs, which are known characteristics of the 6LoWPAN protocol (Jara *et al.*, 2013b).

Depending on the application requirements, two classes of mobility have been defined, they are respectively node mobility and network (or group) mobility. In node mobility, a node moves within the same personal area network (PAN) or between different PANs and runs the mobility mechanism like Mobile IPv6 (MIPv6) regardless of other nodes. MIPv6, as an example of node mobility, causes traffic congestion, increased complexity, increased power consumption and high handover signalling, when all nodes of a group of nodes run MIPv6 mobility management independently (Ha *et al.,* 2010). In contrast, network mobility has become more common for wireless sensor networks (WSN) (Yick *et al.,* 2008) whereby the mobility is considered for the entire low-power personal area network (LoWPAN) network. In 6LoWPAN, a mobile network includes member nodes and an edge router, and only the edge router changes its attachment point on the Internet while the member nodes remain attached to itself (Shelby and Borman, 2011). The IPv6 mobility protocol is further classified into the host-based and network-based mobility, respectively. The host-based mobility requires additional protocol stacks and signalling, resulting in an additional burden for battery power and computation resource in the MNs. Hence, the host-based mobility approach is unsuitable for energy-constrained sensor nodes (SNs) like 6LoWPAN. On the other hand, in the network-based mobility schemes, the mobility of 6LoWPAN MN is handled at the network-side and the MNs are not involved with IP mobility signalling, hence it is not necessary to install additional mobility protocol stacks in the MN or additional signalling exchange (Kim, *et al.*, 2008). For example, in network mobility (NEMO) presented in (Devarapalli *et al.*, 2005), a special mobility agent in the network known as a mobile router (MR) is responsible for handover, exchanging mobility-related signalling messages and mobility management on behalf of the mobile network nodes (MNNs). However, the MR is involved with most of the handover management signalling, hence its energy will certainly drain very fast (Kim, *et al.*, 2008). Therefore, it is more sensible that this responsibility is taken by the network components due to their readily available power, such as in well-equipped networking centers. With this arrangement, the load on MNs could be reduced, and therefore its lifetime could be prolonged. The benefits of the MR architecture have been recognized in the 1990s. Hager *et al.,* (1993) presented a mobile internet router (MINT) that describes a router with a sufficient computational power to perform all necessary communication protocol operations and enable a connectivity for MNNs attached to the MR. The MR maintains continuous connectivity between MNNs inside the mobile network and the home network by means of an appropriate mobility management scheme. The mobile network is connected to the Internet via an IP-IP tunnel between the MR and the home agent (HA) when the MR is far away from the home network. Therefore, it is evident that NEMO enables increased manageability, conservation of bandwidth, reduced signalling, and reduced power consumption as compared to MIPv6. However, this comes at the expense of inefficient route and signalling costs (Goswami, *et al.,* 2013).

As one of the many possible applications, healthcare has formed one of the most attractive research fields that leverage on 6LoWPAN based WSNs. In this thesis, the author considers the hospital wireless sensor network (HWSN) as a case study (Khan and Mir, 2014a) to monitor the patient's health, as the application scenario. This kind of network collects continuously, various vital signals from patients such as heart rate, breath rate, blood pressure, blood oxygen saturation, ear thermometer, body temperature and also the current location of the patient (Hoey, *et al.*, 2012). It is important to keep continuous connectivity between mobile patient node and the hospital wireless network by way of a proper mobility management, this will let the system know the exact location of the patients, and this should be done with minimal loss of packets and with low signalling. Jara *et al.*, (2010a) presented a hospital wireless sensor network based on 6LoWPAN (HWSN6) mobility as a network-based protocol because a low messaging load is exerted due to the reduced number of messages necessary to support mobility. By avoiding reconfiguring IP addresses, the number of messages exchanged with the patient nodes are reduced from 12 messages exchanged in MIPv6 to 6 messages exchanged, which results in reduced MN's loading compared to other IPv6 mobility solutions such as MIPv6. Finally, this protocol considers the features of the architecture employed in hospitals when a solution to node mobility has been defined, and other elements of the architecture are exploited including border router (BR) and backbone to support mobility. Therefore, clinical environment is one of the main scenarios where the mobility for the IoT-based applications exploit these capabilities, in terms of fault tolerance and continuous monitoring of patient's data (Jara *et al.,* 2013b). Thus, the main objective of this thesis is to present an efficient network mobility management for a hospital environment that will enable continuous connectivity between the patient node with its HA for transmitting vital signals. The protocol shall minimize involvement of the patient node, this is done by reducing the interaction of the patient node in the network in the mobility protocol.

1.2 Problem Statement and Motivations

As has been highlighted earlier, the HWSN is a suitable solution for e-Health communication that provides real-time monitoring of medical information for patients. It especially handles low-cost and low-power devices suitable for medical sensors used on mobile patients, this can provide effective support for people suffering from chronic diseases or patients during emergencies (Bui *et al.,* 2012). From the survey of existing mobility solutions, it was concluded that the existing schemes still suffer from the extra signalling cost and packet loss during handover and without continuous connectivity, which is not acceptable when some vital and critical data are being transferred (Khan and Mir, 2014a). Hence, the efficient customization in energy efficient and reliable transmission of network mobility management for health data based on 6LoWPAN network is required to improve the quality of healthcare, potentially save the patient's life.

When a set of 6LoWPAN SNs moves together, NEMO solution is better than host mobility, MIPv6 protocol, running each node independently, because it minimizes complexity and number of handover signalling messages of individual hosts, and power consumption of mobile hosts. NEMO protocol has been developed based on the experiences gained from the MIPv6 standardization, and therefore many of the functionalities are actually extensions of MIPv6 as a host-based mobility, which is not suitable for 6LoWPAN. However, this thesis design parameters such as number of MNNs, number of handovers, and packet generation rate from MNNs for NEMO in 6LoWPAN area are analyzed. Hence, even though NEMO is an excellent approach for managing a mobile network, but there are some shortcomings to manage mobility in 6LoWPAN area.

- The transmission of control information in the handover process of NEMO consumes a large amount of energy and the increasing of handover signalling messages increases handover signalling costs, handover delay, packet loss, and causes traffic congestion (Angadi and Shet, 2013).

- After a successful completion of the binding process, a tunnel is established between the MNNs of the MR and its respective HA to achieve a global connectivity with mobile network (MNN-MR-BR-HA or MNN-MR-HA path). When the MR receives the packets from MNNs, it encapsulates them and sends them to the HA through the tunnel. When the MR receives a packet from a foreign agent (FA) or HA, it decapsulates it and sends it to the MNNs through the tunnel. This imposes an extra burden on the tunnel (MR-HA path) especially when there is a heavy traffic, hence route optimization is necessary for NEMO.

- There is a heavy traffic at the MR due to network management, data transmission, handover signalling messages and tunnelling process (Petander *et al.,* 2006). Since all traffic goes through the MR in a mobile network, overloading at the MR is critical, as a result the MR depletes its energy very fast and die out soon after, which causes a bottleneck problem and completely disconnects. If the MR fails, the connectivity between the network and MNNs will be severed completely. In basic NEMO, modern and powerful devices like smart phones or BRs with assured energy availability are likely candidates to choose as an MR. However, in the 6LoWPAN mobile network, all devices are characterized with energy constraints not having access to permanent energy resources. Figure 1.1 shows the bottleneck at MR in NEMO protocol that will lead to additional packet delays, or even packet losses. Various works have shown a good agreement with traffic congestion on MR and bottleneck problem (Devarapalli *et al.*, (2005), Moceri (2006), Bag *et al.*, (2009a), Dinakaran and Balasubramanie (2010), and Mosa *et al.*, (2012)). To this date, there are very few works that has been reported to optimize energy consumptions at the MR by way of handling and optimizing the mobility signalling messages.

Khan and Mir (2014a), from their survey on mobility management, concluded that existing schemes still suffer from extra signalling and packet loss during handover, which is not acceptable when some critical data is being transferred.

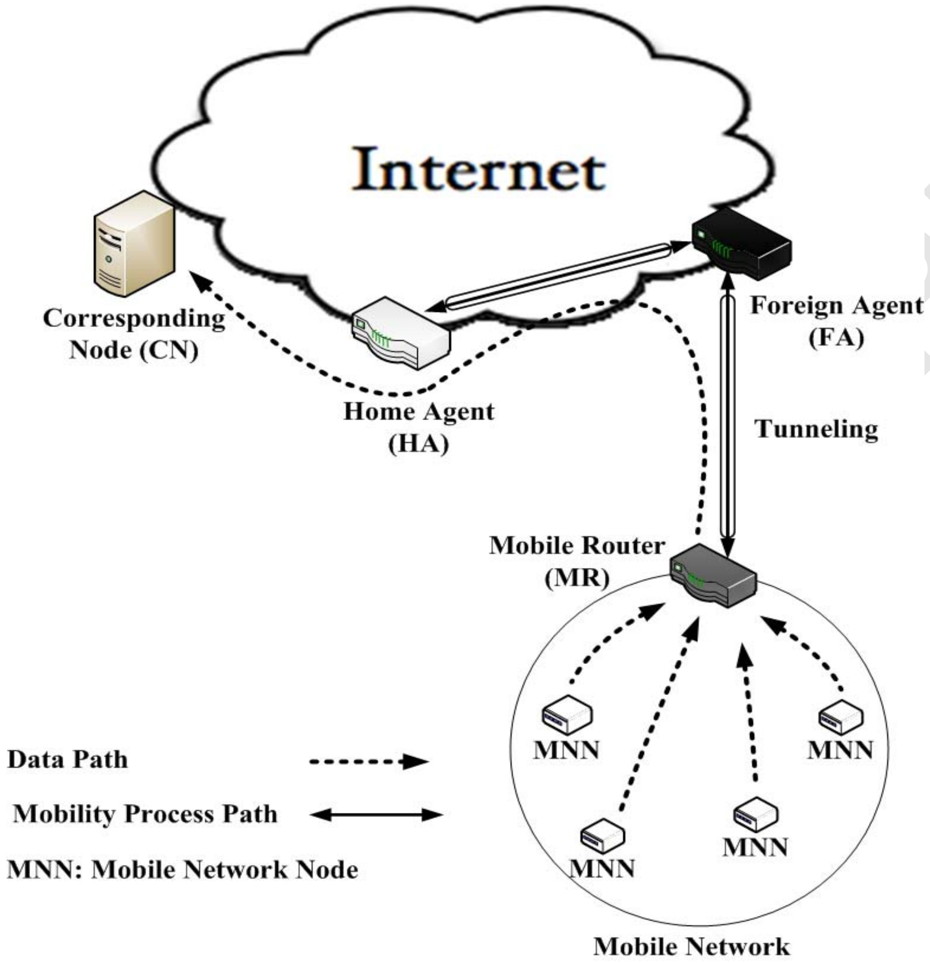

Figure 1.1: Network mobility (NEMO) scenario

1.3 Research Aims and Objectives

The aim of this thesis is to obtain an efficient NEMO mobility solution with the following features. (1) Network-based protocol to support 6LoWPAN; (2) Network mobility to support mobile patients; (3) Intra-PAN mobility to support the hospital environments; (4) Support low handover signalling cost, low handover delay, low end-to-end packet delay, low packet loss, and low energy consumption to keep continuous connectivity between MNs and a backend server to exchange the vital signals. Based on the problem statements stated previously, the following specific objectives are identified.

1. To reduce the handover signalling costs and handover delay through a handover process of NEMO mobility by HWSN6 solution. Handover signalling is one of

the major design considerations and performance measure to improve the handover performance like packet loss and keep connectivity.

2. To reduce traffic congestion at MR and end-to-end packet delay by way of a message-scheduling algorithm that is based on tunnelling for NEMO route optimization of packets travelling from MNNs to CN.

3. To improve the energy saving of MR in order to prolong its lifetime through a selective optimal MR algorithm. This is achieved by way of distributing the role of MR among all the MNNs to balance network energy.

By developing an optimized signalling protocol during handover and route optimization during tunnelling process, an efficient mobility management for 6LoWPAN mobile networks can be achieved. It also prolongs the MR lifetime to maintain continued connectivity for mobile networks when exchanging the critical data.

1.4 Research Scope and Limitations of Research

The scope of research work is summarized in figure 1.2 with the bold blue color lines indicating the research path. The aim of this thesis is to develop the NEMO solution by reducing the overload at 6LoWPAN network in smart buildings, particularly a hospital environment, to keep connectivity between mobile network and the Internet. As shown in figure 1.2, this work focuses on three main research issues: minimization of handover signalling to reduce the overhead by consideration on mobility control messages, route optimization in tunnelling process of network mobility, and managing the MR based on battery level. Additionally, the MR as a coordinator in the 6LoWPAN mobile network will be evaluated to improve its residual energy. The performance metrics such as signalling cost, end-to-end packet delay, packet loss, traffic congestion on MR will be investigated. OMNeT++ simulator has been developed to evaluate this network model, linked with Contiki, to process the adaptation layer functionalities. The performance metrics such as traffic congestion at MR, signalling cost, end-to-end packet delay, packet loss and the energy consumption of MR during mobility process, are modeled and simulated using OMNeT++ simulator.

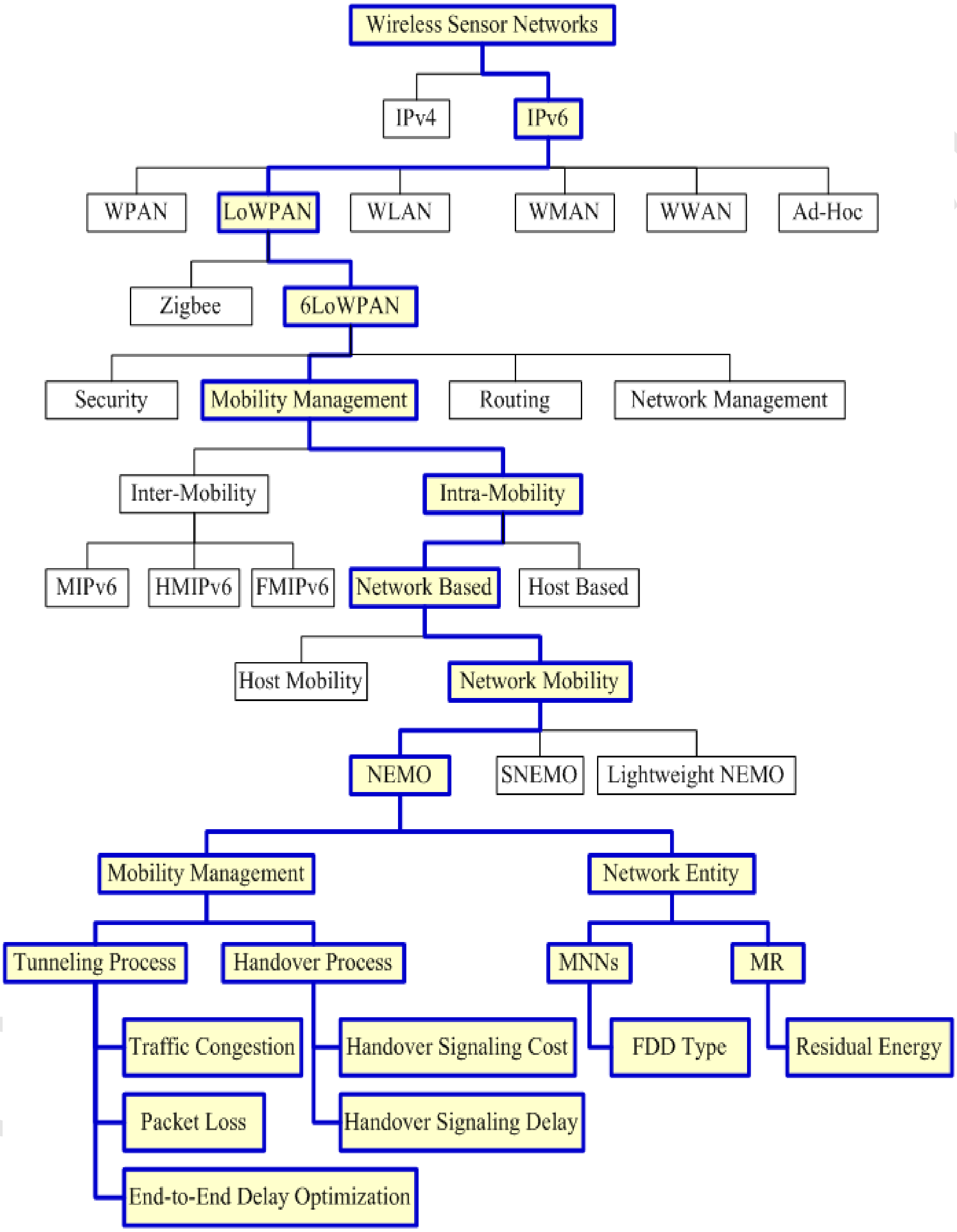

Figure 1.2: Chart of research

However, the following assumptions and limitations are defined for the mobility protocol to manage handover process.

1. A 6LoWPAN node should be reachable by another 6LoWPAN node or a global network node even when it is moving from one attachment point to another,

2. The smart building in this work is clinic, hospital, nursing home, etc. to provide smart control of indoor environmental systems like patients that is served with WSNs. This technology enables doctors and patients to connect remotely and share information through wireless tools,

3. Each domain is a LoWPAN area with a short transmission distance between MNNs for mobile network and BRs,

4. In this scenario a mobile network with attached body sensors are set up to monitor the vital measurement. Using portable monitoring systems based on WSNs makes it possible to get an efficient medical service and provides freedom for patients,

5. All MNNs, especially MR are of type full-function device (FFDs). The FDD type nodes support full functions like managing handover process and capable of operating as a PAN coordinator,

6. Even though security is important for the mobility management in wireless networks to protect the patient's information, it is not considered in this thesis since HWSN6 has already supported it. On the other hand, the other 6LoWPAN research issue such as security concern is out of the scope of this thesis.

1.5 Research Contributions

Hence, the main contributions of this thesis can be summarized as follows:

- **An improved handover process in NEMO, to achieve objective 1:** The NEMO protocol provides basic network mobility functionality on MIPv6 protocol. This contribution results in a higher efficiency and reduces signalling cost compared with host mobility. By way of a logical extension of the HWSN6 operation at the MR, this proposed protocol avoids reconfiguring IP addresses to minimize MR's overload, the handover signalling cost inside the network and handover signalling delay, respectively.

- **A message-scheduling algorithm for tunnelling process, to achieve objective 2:** The route optimization is proposed in the tunnelling process of mobility management. It considers message scheduling from MNNs after binding update (BU) is completed. By way of this solution, efficient data transmission to minimize MR overload can be maintained, and this tends to improve performance metrics like end-to-end packet delay and packet loss.

- **An implementation of the selective optimal MR algorithm to achieve objective 3:** This is an energy solution based on energy-balancing to improve energy saving of MR in NEMO. It searches for an MNN with the largest energy reserves when the MR residual energy drops below the certain threshold to replace it with the new selected MNN.

- **A simulation model to design, test, simulate, and analyze the proposed scheme:** Throughout the simulation, a 6LoWPAN adaptation layer has been developed by using Contiki in OMNeT++ simulator. This contribution is important to provide a 6LoWPAN simulation platform in OMNeT++ for the proposed network mobility protocol and future 6LoWPAN-related works. With this simulator, the behaviors and characteristic of the protocol can be studied without the need to build a real network. Various parameters were set according to the purpose of the simulation to observe the network response.

- **Analytical model:** This work was validated by using the MIPv6 for our proposed scheme. The performance metrics like tunnelling costs is investigated.

1.6 Thesis Organization

This thesis is organized into five chapters as follows:

The first chapter presents the research topic as a background of mobility and highlight the research problem, research motivations, set the objectives, define the scope and limitations, and describes the thesis organization.

The second chapter presents a review of the literature on and around 6LoWPAN. The mobility protocols and architecture are briefly described. Most of the relevant previous works have been critically reviewed and their strengths points and limitations are highlighted.

The third chapter describes the research methodology which explains the proposed scheme in detail for efficient NEMO mobility management to achieve the research objectives and analytical model.

Chapter 4 presents the results and discussions on the evaluation of the mobility protocol against the design parameters, and the results in order to show an efficient mobility management. The performance of the proposed scheme is evaluated and compared with other works in handover signalling cost, handover delay, end-to-end packet delay, packet loss, and energy consumption.

Finally, the last chapter summarizes and highlights the thesis based on the results presented in this thesis. The key points of thesis and contributions of all proposed schemes are summarized. This gives some recommendations for future research in this area.

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