Sang-Joong Jung

PERSONAL MACHINE-TO-MACHINE (M2M) HEALTHCARE SYSTEM WITH MOBILE DEVICE IN GLOBAL NETWORKS
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**Abstract**

This thesis describes the development of a personal machine-to-machine (M2M) healthcare system that is both flexible and scalable. Based on the IPv6 protocol, the system can be used over a low-power wireless personal area network (6LoWPAN). Since a hierarchical network structure offers excellent accessibility, the system is applicable both to local and international healthcare services. To further enhance scalability and reliability, the proposed system combines 6LoWPAN with mobile techniques, depending on whether the sensor is located inside or outside the range of a wireless sensor network (WSN).

Employing wearable low-power sensors, the system measures health parameters dynamically. For wireless transmission, these sensors are connected to an M2M node either through the internet or through an external IPv4/IPv6-enabled network. The applicability of the IEEE 802.15.4 and 6LoWPAN protocols to wide area networks were verified in practical tests using an M2M gateway.

To assess the physical health of an individual, the system uses heart rate variability analysis in time and frequency domains. Acquired data are first stored on a server for analysis. Results of the analysis are then automatically sent to Android-based mobile devices carried by the individual or appointed healthcare providers. In this way, mobile techniques are used to support remote health monitoring services.

This personal M2M healthcare system has the capacity to accurately process a large amount of biomedical signals. Moreover, due to its ability to use mobile technology, the system allows patients to conveniently monitor their own health status, regardless of location.

**Keywords:** 6LoWPAN, autonomic nervous system, global healthcare service, health condition, heart rate variability, machine-to-machine, mobile technique
Jung, Sang-Joong. Henkilökohtainen, globaaliverkossa mobiililaitteiden välillä toimiva terveydenhoitojärjestelmä.
Oulun yliopiston tutkijakoulu; Oulun yliopisto, Teknillinen tiedekunta, Sähköteknikan osasto, Optoelektronian ja mittautsteeknikan laboratorio

Oulun yliopisto, PL 8000, 90014 Oulun yliopisto

Tiivistelmä
Tutkimuksessa kehitetään henkilökohtainen mobiililaitteiden välillä toimiva (M2M) terveydenhoitojärjestelmä, joka mahdollistaa joustavan ja skaalatuksen potilaan terveyden monitoroinnin. Perustuen IPv6-protokollaan, sovellusta voidaan käyttää matalatehoisen langattoman 6LowPAN-verkon yli. Koska hierarkkinen verkkorakenne tarjoaa erinomaisen saavutettavuuden, järjestelmän kapasiteetti riittää paitsi kaupungin sisäisten myös kansainvälisten terveyspalvelujen järjestämiseen. Skaalattavuuden ja luotettavuuden vuoksi ehdotettu järjestelmä yhdistelee 6LowPAN-teknikkaa mobiiliteknologiaan riippuen siitä onko sensori langattoman sensoriverkon kuuluu


Tämä henkilökohtainen M2M-kommunikointiin perustuva terveydenhoitojärjestelmä kykenee käsittelemään suuria laajavälissä tulevia biolääketieteellisiä signaleja. Lisäksi kyky käyttää mobiiliteknologiaa tekee järjestelmästä potilaiden välinen viestintä, mobiilitekniikka, sykevaihtelu, terveydentila

Asiakas: 6LoWPAN, autonominen hermosto, globaali terveydenhuoltopalvelu, koneiden välinen viestintä, mobiili teknikka, sykevaihtelu, terveydentila
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Special thanks to Professor Wan-Young Chung for giving me an opportunity to work on this research in USN laboratory and for introducing and guiding me patiently throughout the completion of this dissertation. His kindness and consideration will remain forever grateful to me. This work would not have been possible without the encouragement, understanding, guidance, and mentoring from him. I would also like to Professor Esko Alasaarela, for his understanding, encouragement and guidance throughout the work of this thesis. His wide knowledge and technical thinking have been of great value to me.

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my son, Sin-Hyeok, and my parents for their encouragement, patience, and trust in me. Thank you all. Standing on a new start, I pledge that my challenges and passions for this research will contribute valuable saving and relieving for people all over the world in the future.

Oulu, October 2013

Sang-Joong Jung
### List of terms, symbols and abbreviations

<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>ADC</td>
<td>Analog-to-Digital Converter</td>
</tr>
<tr>
<td>ANS</td>
<td>Autonomic Nervous System</td>
</tr>
<tr>
<td>AP</td>
<td>Access Point</td>
</tr>
<tr>
<td>API</td>
<td>Application Programming Interface</td>
</tr>
<tr>
<td>BAN</td>
<td>Body Area Network</td>
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<tr>
<td>BER</td>
<td>Bits Error Rate</td>
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<tr>
<td>BPF</td>
<td>Band-Pass Filter</td>
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<tr>
<td>BSN</td>
<td>Body Sensor Network</td>
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<tr>
<td>CSMA</td>
<td>Carrier Sense Multiple Access</td>
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<tr>
<td>dB</td>
<td>Decibels</td>
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<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>ECG</td>
<td>Electrocardiogram</td>
</tr>
<tr>
<td>ETSI</td>
<td>European Telecommunication Standards Institute</td>
</tr>
<tr>
<td>EUI</td>
<td>Extended Unique Identifier</td>
</tr>
<tr>
<td>FI</td>
<td>Future Internet</td>
</tr>
<tr>
<td>GHz</td>
<td>Gigahertz</td>
</tr>
<tr>
<td>GSM</td>
<td>Global System for Mobile Communications</td>
</tr>
<tr>
<td>GPI</td>
<td>Graphical User Interface</td>
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<tr>
<td>HF</td>
<td>High Frequency</td>
</tr>
<tr>
<td>HPF</td>
<td>High-Pass Filter</td>
</tr>
<tr>
<td>HR</td>
<td>Heart Rate</td>
</tr>
<tr>
<td>HRV</td>
<td>Heart Rate Variability</td>
</tr>
<tr>
<td>Hz</td>
<td>Hertz</td>
</tr>
<tr>
<td>ID</td>
<td>Identification</td>
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<tr>
<td>IDE</td>
<td>Integrated Development Environment</td>
</tr>
<tr>
<td>ICMPv6</td>
<td>Internet Control Message Protocol Version 6</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
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<tr>
<td>IETF</td>
<td>Internet Engineering Task Force</td>
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<tr>
<td>IoT</td>
<td>Internet of Things</td>
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<tr>
<td>IP</td>
<td>Internet Protocol</td>
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<tr>
<td>IPSO</td>
<td>IP for Smart Objects</td>
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<tr>
<td>IPv4</td>
<td>Internet Protocol version 4</td>
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<tr>
<td>IPv6</td>
<td>Internet Protocol version 6</td>
</tr>
<tr>
<td>ISA</td>
<td>International Society of Automation</td>
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</table>
ISM   Industrial, Scientific, and Medical
IT    Information Technology
KB    Kilobyte
Kbps  Kilobits per Second
LAN   Local Area Network
LF    Low Frequency
LOAD  6LoWPAN Ad Hoc On-Demand Distance Vector Routing
LPF   Low-Pass Filter
LoWPAN Low-Power Wireless Personal Area Network
MAC   Media Access Control
MB    Megabyte
Mbps  Megabits per Second
MCU   Micro Controller Unit
MHz   Megahertz
MTU   Maximum Transmission Unit
M2M   Machine-to-Machine
NEMO  Network Mobility
nesC  Network Embedded System C
NN    Normal-to-Normal
OHA   Open Handset Alliance
OS    Operating System
PAN   Personal Area Network
PC    Personal Computer
PCB   Printed Circuit Board
PDA   Personal Digital Assistant
PHY   Physical Layer
pNN50 Proportion derived by Dividing NN50 by Total Number
PPG   Photoplethysmogram
PSD   Power Spectrum Density
R     Ratio
RF    Radio Frequency
RFC   Request for Comments
RMSSD Root Mean Square Successive Difference
RS-232 Recommended Standard 232
SDK   Software Development Kit
SDNN  Standard Deviation of All Normal RR Intervals
SI    Stress Index
10
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
</tr>
<tr>
<td>SOA</td>
<td>Service Oriented Architecture</td>
</tr>
<tr>
<td>SpO₂</td>
<td>Oxygen Saturation</td>
</tr>
<tr>
<td>TCP/IP</td>
<td>Transmission Control Protocol/Internet Protocol</td>
</tr>
<tr>
<td>TinyOS</td>
<td>Tiny Micro Threading Operating System</td>
</tr>
<tr>
<td>UART</td>
<td>Universal Asynchronous Receiver/Transmitter</td>
</tr>
<tr>
<td>UDP</td>
<td>User Datagram Protocol</td>
</tr>
<tr>
<td>USB</td>
<td>Universal Serial Bus</td>
</tr>
<tr>
<td>USN</td>
<td>Ubiquitous Sensor Network</td>
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<tr>
<td>V</td>
<td>Voltage</td>
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<tr>
<td>VLF</td>
<td>Very Low Frequency</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless Local Area Networks</td>
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<tr>
<td>WSN</td>
<td>Wireless Sensor Networks</td>
</tr>
<tr>
<td>3G</td>
<td>3rd Generation Mobile Telecommunications</td>
</tr>
<tr>
<td>6LoWPAN</td>
<td>IPv6 over Low-Power Wireless Personal Area Networks</td>
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List of original papers


Paper I describes the design and implementation of wearable healthcare nodes for an ambient wireless sensor network, offering good patient mobility in an entire building or house. These wearable healthcare nodes consist of a general purpose wireless sensor node, a chest-belt sensor with integrated ECG and accelerometer sensors and a wrist-belt sensor with a reflectance oximeter. In addition, heart rate variability analysis based on time and frequency domain features was introduced to provide data for the estimation of negative emotional states.

Paper II concentrates on a new IP-USN healthcare monitoring technique implemented in 6LoWPAN. IP-USN healthcare monitoring systems support location-independent monitoring of patient health over the internet. This paper describes wireless measurements of PPG signals, heart rate and oxygen saturation conducted to test the LOAD routing protocol between a 6LoWPAN node and a 6LoWPAN gateway. Also discussed are key 6LoWPAN techniques to efficiently support IPv6 over 802.15.4 links. These developments make IP attractive for use in low-power devices from handhelds to instruments.
Paper III describes a wearable device for measuring oxygen saturation. This low-power consumption device is based on reflectance pulse oximetry. Successful operation was demonstrated in a ubiquitous healthcare system by performing measurement, communication and monitoring functions in a wireless sensor network. Some of the measurement scenarios produced distorted waveforms containing noise that affected the system’s reliability.

Paper IV presents a wireless health monitoring system realized using multi-hop body sensor networks on a ubiquitous sensor network platform. This paper introduces the design and development of a wearable u-healthcare monitoring system using integrated ECG, accelerometer and oxygen saturation (SpO₂) sensors. Biomedical signals from multiple patients were relayed wirelessly to a base-station using a multi-hop routing scheme.

Papers V and VI describe the concept of a new patient health monitoring application based on 6LoWPAN. These papers presented and tested PPG and ECG sensors designed to wirelessly measure ECG, PPG and 3-axis accelerometer signals in 6LoWPAN and IP network environments. Also discussed were key ideas for establishing a 6LoWPAN network that provides efficient support for IPv6 over the IEEE 802.15.4 protocol for healthcare applications. HR distribution and the ratio of LF and HF power components were verified by analysis of ANS balance diagram for estimation of health.

Paper VII studies a wireless M2M healthcare solution that employs mobile devices in a global network. Combining 6LoWPAN and mobile communication techniques allows us to significantly extend network reach and enhance the accessibility of M2M devices. The designed solution measured PPG signals and transmitted them to a server PC over a mobile IP-enabled internet. The solution offered a mobile healthcare service based on an Android application running on a Samsung Galaxy S device with wireless internet access.

The author defined the research plan, carried out the literature review and wrote the manuscript presented in Papers I-VII. Experiments and measurements were conducted by the author in association with the co-authors. The manuscript for Paper IV was produced by the author with the kind help of the co-authors.
# Table of contents

Abstract

Tiivistelmä

Acknowledgements 7

List of terms, symbols and abbreviations 9

List of original papers 13

Table of contents 15

1 Introduction 17

1.1 Overview and motivation ................................................................. 17

1.2 Challenges and contributions ......................................................... 18

1.3 Outline of the dissertation .............................................................. 22

2 Literature review and related work 25

2.1 Wireless sensor network for a healthcare system ............................... 25

2.2 IPv6 over LoWPAN (6LoWPAN) .................................................... 26

2.3 Android mobile technology ............................................................. 30

3 Machine-to-machine (M2M) technology 33

3.1 M2M communications .................................................................... 33

3.2 Mobile-based M2M healthcare system ............................................ 34

3.2.1 System architecture ................................................................. 35

3.2.2 Benefits of M2M networks ....................................................... 36

4 System design and implementation 39

4.1 Hardware design ............................................................................ 39

4.1.1 Health sensors .......................................................................... 39

4.1.2 M2M devices ........................................................................... 41

4.1.3 Android mobile device ............................................................ 42

4.2 Software design ............................................................................. 43

4.2.1 TinyOS programming .............................................................. 43

4.2.2 Gateway tunnelling ................................................................. 44

4.2.3 Server program ...................................................................... 45

5 Results and performance analysis 49

5.1 Experimental setup ....................................................................... 49

5.2 Analysis and evaluation of health condition ................................... 50

5.3 Mobile healthcare service ............................................................. 55

6 Discussion 59

7 Summary 61

References 63

15
1 Introduction

1.1 Overview and motivation

Information and communications technologies are transforming our social interactions, our lifestyles and our workplaces. One of the most promising applications of information technology is healthcare and wellness management. Healthcare is moving from reactive responses to acute conditions to a proactive approach characterized by early detection, prevention and long-term healthcare management. In this framework, health condition monitoring and wellness management are seen as significant contributors to individual healthcare and wellbeing. This is particularly important in developed countries with a significant aging population, where information technology can be employed to significantly improve the management of chronic conditions and, thereby, overall quality of life.

Continuous or even occasional recording of biomedical signals is particularly critical for the diagnosis and treatment of cardiovascular diseases [1–4]. For example, continuous recording of an electrocardiogram (ECG) or photoplethysmogram (PPG) by a wearable sensor provides a realistic view of a patient’s heart condition by tracking such factors as high blood pressure, stress [5–6], anxiety, diabetes and depression [7–8], during normal daily routines.

Further, automated analysis of such recorded biomedical signals supports doctors in their daily work and allows the development of warning systems. This brings several benefits, such as decreased healthcare costs, by increasing health observability, collaboration among doctors and doctor-to-patient efficiency [9–11]. Moreover, continuous monitoring serves to increase early detection of abnormal health conditions and diseases, offering a way of improving patients’ quality of life [12–13].

Nowadays, more attention is focused on the prevention and early detection of diseases as well as on optimal management of chronic conditions. These functions are often augmented by new location-independent technologies. In order to fully realize a pervasive or ubiquitous environment, personal area networks (PAN) must be connected to internet protocol (IP)-based networks.

Such integration enables resource sharing within networks, maximizing the utilization of available resources. In addition, communication with the individual nodes in a network requires an efficient addressing mechanism.
A working group of the Internet Engineering Task Force (IETF), known as 6LoWPAN, is currently working to standardize internet protocol version 6 (IPv6) to facilitate data transmission over IP-based wireless networks [14–15]. Due to their inherent properties, these networks provide better coverage, fault tolerance and more robust behaviour. As the prime beneficiary of these new strategies, IP-based wireless networks are a catalyst for accelerating M2M service innovation, helping to identify hidden growth opportunities in M2M services. The evolution of M2M hinges on the development of wireless sensor networks (WSN) based on IPv6 techniques [16]. A key advance is the adoption of IPv6 with its efficient addressing mechanism, replacing the current IEEE 802.15.4 standard. Extending the new standard to every node/device enhances the quality of data transmission and expands the coverage of healthcare services. Thus, a global M2M network based on a WSN and incorporating healthcare applications can be used to augment the traditional healthcare system. A network of this type has the potential to provide new advantages, including accessibility and ease of measurement, for patients with a global IPv6 address and a mobile communication device [17–18].

In addition, new generation mobile phones have an important impact on the development of such healthcare systems, as they seamlessly integrate a wide variety of networks (3G, Bluetooth, wireless LAN and GSM) through access points (APs), thereby providing an opportunity to transmit recorded biomedical signals to a central server in a hospital [19–20]. As a result, continuous monitoring of biomedical signals will no longer be restricted to the home environment.

This thesis presents a new attempt of extending an IP-based sensor network supporting 6LoWPAN and mobile communication into a global personal M2M healthcare system. Utilizing IPv6 over IEEE 802.15.4 represents a special match of the two technologies, allowing the use of mobile devices for global access to healthcare monitoring applications. As each 6LoWPAN node is assigned a global IPv6 address, external hosts can directly communicate with these nodes, offering higher accessibility and an epoch-making network extension. Thus, the system serves to improve the coverage of healthcare services through the flexibility and scalability provided by IPv6 addressing.

1.2 Challenges and contributions

A number of challenges face the developers of WSNs, including support for M2M technology to allow direct exchange of information between machines, which, in
turn, enables systems to manage themselves without human intervention [21]. A typical IEEE 802.15.4-based sensor network protocol uses a non-IP network layer protocol in limited areas, where transmission control protocol/internet protocol (TCP/IP) is not applicable. However, future applications of WSN consist of thousands of nodes, and IP-based networks may be connected to other networks via the internet [22]. This can be achieved by the effective use of IPv6 standards. The emergence of 6LoWPAN can be treated as the beginning of a new generation of M2M networks. An equally important development has taken place in mobile services. Rapid developments in mobile technologies allow mobile devices to monitor and communicate with embedded devices. Moreover, due to their ease of use and falling costs, mobile devices are increasingly used in a range of applications, thereby contributing to producing great changes in today’s lifestyle. During the past decade, the development of wireless mobile and information technologies (IT) has helped to extend the concept of ubiquitous coverage to new segments of society.

Thus, many applications that were initially available at a fixed location only have been transformed into ubiquitous applications, capable of being used wirelessly and flexibly at anytime, anywhere. The same trend has been observed in the medical field. Over the years, many telemedicine and healthcare related societies and authorities have turned to wireless technologies to overcome the poor mobility of desktop PC-based healthcare monitoring systems. As a result, the possibility to monitor biomedical signals using a mobile device is no longer an unachievable dream. Recent technological advances and the ever-increasing number of patients suffering from chronic diseases inspired the idea of this dissertation, where wireless technologies are applied to help patients improve their situation [23]. These technologies allow drawing inferences in real-time from a range of behavioural data made available via a mobile device, such as a phone. Users then receive feedback relating to these behaviours, enabling them to make better everyday lifestyle choices and, ultimately, to better manage their health.

Although many healthcare systems of this type are already in existence, they tend to have certain weaknesses. One of these is measurement area. Measurement systems are often too large to carry and signal communication cables are not always easy to move. Consequently, measurement signals can only be recorded near the device itself. Another problem is measurement coverage. To facilitate the detection of the biomedical signals, measurements are generally conducted on the patient’s body, causing inconvenience. Moreover, specific parts of body are often
fixed and cannot be moved or used during the measurement, restricting the patient’s motions and movements.

An additional major problem is that sensor devices are vulnerable to noise, and wire cables are particularly prone to wear and damage. Analog circuit and cable movements are a significant source of noise, and analog data transmission is responsive to changes in peripheral conditions. Though the concept of using global M2M based healthcare system in the context of WSN adds to the network new properties such as mobility and interoperability, the literature and our general understandings of global M2M healthcare system has been greatly affected by the legacy of the theory and test-bed based projects. Until now, the theory and test-bed based projects concerning purely global M2M healthcare system has been limited.

Motivated by these facts, this dissertation has been focused on establishing a healthcare-orientated M2M network combined with their widespread use in wireless technology to closely monitor changes in patient condition using comfortable biomedical sensors providing relevant biomedical information. This means the proposed system support the highest level of wireless communication based healthcare integration system as a result of the specific well-designed methodologies. The proposed system can improve the expansion of healthcare service coverage through 6LoWPAN and mobile technology. Mobile devices, such as those used by the system, are almost universally IP-enabled, currently making up the largest body of devices belonging to the Internet of Things (IoT).

Thus, the main objective of this dissertation can be summarized as follows: to propose an approach to healthcare services based on conducting wireless measurements via 6LoWPAN and mobile networks using wearable health sensors. The inherent advantages of the approach include improving mobile personalized sensing and extending the network scale to allow the timely and reliable communication of measured data. This dissertation can be thought to make four special contributions:

1. 6LoWPAN is studied in order to develop a WSN based on the IPv6 technique. In fact, the 6LoWPAN technique provides a new attempt of the extension of an IP-based sensor network environment at the different global coverage areas for the healthcare application with the IPv6 technique. A key advance with the adoption of IPv6 is its efficient addressing mechanism, which replaces the current IEEE 802.15.4 standard. The M2M gateway provides reliable IPv6 communication to transmit a patient’s biomedical signals to a
doctor or server via the Internet. Utilizing IPv6 over the IEEE 802.15.4 is a special match of the two technologies. Extending the new standard to every node/device enhances the quality of data transmission and expands the coverage of healthcare services (see Sec 2.2).

2. A global M2M network is implemented for the network performances under several different scenarios in healthcare applications. Therefore, external hosts directly communicate with the M2M nodes because each M2M node is assigned a global IPv6 address, thereby supporting higher accessibility and epoch-making network extension. Practical tests of network performance with different scenarios are conducted in global areas. The proposed system includes measurement of health parameters, wireless and wire communications, health condition monitoring in a server and a mobile with a global reach (see Sec 3.2).

3. A mobile healthcare monitoring system is developed for a novel M2M healthcare solution based on Android mobile devices. An Android-based smartphone is used as monitoring terminal due to its smart functions and computer-like features. After testing the monitoring application by the Android emulator, the monitoring application is easily installed on the Android mobile via a direct cable from PC or at the Android markets store wirelessly. Utilizing a smartphone, the system has the capacity to provide healthcare services not only in the home or hospital environments, but practically anywhere (see Sec 5.3).

4. Such health parameters as ECG, PPG and activity data can be recorded and analyzed, and their accuracy and usefulness for diagnosis can be determined. In the analysis of HRV signals, there are two different kinds of methods, which are time domain and frequency domain analysis. To detect stress factor, this dissertation interprets HR distribution graph, SDNN, RMSSD, pNN50, and SI by analyzing the HRV signals in the time domain. From the frequency domain analysis, negative emotions such as anxiety and hostility are verified by using the PSD analysis with spectral components such as VLF, LF, HF, ratio of LF/HF, and ln values of LF and HF. These analysis results can then be used to offer further insight into the natural cause and progression of diseases and to enhance the accuracy of early symptom detection (see Sec 5.2).
To break down the overall objective into smaller and manageable parts, three research questions have been arranged. The main research question in this dissertation is:

Research Question 1: Does standards-based M2M devices provide a feasible system in healthcare applications for present and future wireless sensor network architectures?

From this main research question, two more research sub-questions are derived to help break down the overall dissertation into smaller pieces. The research sub-questions are:

Research Question 2: Can global M2M system achieve the reliable network performance connected to external networks in wide measurement area for high interoperability?

Research Question 3: How can pervasive and user-oriented healthcare system be achieved through the use of existing infrastructures?

These three questions are the main motivation for seeking better achievements of user-oriented healthcare services with maximum mobility and flexibility to the patients who are in urgent need of such services in this dissertation.

1.3 Outline of the dissertation

While the growth of healthcare systems has centred on infrastructure and usage, little work has been done to test and validate the use of wearable sensors in a global network environment. The aim of this dissertation is to implement a personal M2M healthcare solution involving an Android device in a global network. A mobile healthcare sensing method is hypothesized, including wearable health sensors for chronic or recovering patients to record changes in biomedical signals via an IP-enabled WSN. In addition, communication architecture for a personal M2M healthcare system relying on 6LoWPAN and mobile techniques is introduced as a way of increasing the coverage of the service. For these reasons, the proposed system is fully functional in a global M2M network, extending its application base to providing relevant biomedical information and to monitoring changes in patient condition using comfortable biomedical sensors in conjunction with M2M devices.
The content of this thesis can be summarized as follows:

Chapter 2 presents a literature review and discusses related work focusing on M2M healthcare solutions. It also presents techniques associated with WSN and 6LoWPAN as well as mobile technologies that are applicable to M2M healthcare systems.

Chapter 3 describes how M2M technology can be enhanced by the use of IP-based wireless networks and mobile communication. This requires using an efficient addressing mechanism that assigns an address to every device.

Chapter 4 presents the design and implementation of the personal M2M healthcare solution developed during this work. This section introduces the architecture of the system and discusses some major design principles and tools developed for the measurement of biomedical signals and for IP-based global communication. In addition to this, an Android mobile device is presented to support personal mobile healthcare monitoring services, providing a complementary measurement for continuous health parameter monitoring.

Chapter 5 presents experimental results of using the developed system in a global network, with a focus on experiment scenarios and performance analysis. Also presented is a mobile healthcare monitoring service involving the use of the Android-based smartphone.

Chapter 6 and Chapter 7 provide discussion and summary of this thesis.
2 Literature review and related work

2.1 Wireless sensor network for a healthcare system

WSN is one of the fastest growing technologies in ubiquitous networking today. Standardization efforts, such as IEEE 802.15.4 [24–27], are geared to reduce costs, provide device customizability for diverse applications and create standards for interoperability. The IEEE 802.15.4 standard was developed to address a demand for low-power and low-cost in low-rate wireless personal area networks (LR-WPAN). Dealing with low data rates, IEEE 802.15.4 offers very long battery life (months or even years) and very low complexity. The IEEE standard 802.15.4 defines the physical layer (PHY) and medium access control (MAC) sub-layer specifications for LR-WPAN in the 2.4 GHz and 868/915 MHz bands. A free license to use the industrial, scientific and medical (ISM) 2.4 GHz band is available worldwide, while the ISM 868 MHz and 915 MHz bands are only available in Europe and North America, respectively. A total of 27 channels with three different data rates are allocated in IEEE 802.15.4, including 16 channels with a data rate of 250 Kbps in the 2.4 GHz band, 10 channels with a data rate of 40 Kb/s in the 915 MHz band and 1 channel with a data rate of 20 Kb/s in the 868 MHz band. Channel sharing is achieved using carrier-sense multiple access (CSMA), and acknowledgments are provided for reliability. Addressing modes for 64-bit (long) and 16-bit (short) addresses are provided with unicast and broadcast capabilities. The main characteristics of WSN devices are small physical size, low-power consumption, limited processing power, short-range communication capability and small storage capacity. [Paper I]

A number of studies and projects have focused on novel ubiquitous healthcare systems utilizing WSN technology to simplify methods of monitoring and treating patients. A case in point is the MobiHealth [28] project, which developed a system for ambulant patient monitoring over public wireless networks based on a body area network (BAN) [29–32]. Another example is the Ubiquitous Monitoring Environment for Wearable and Implantable Sensors project (UbiMon) [33] at Imperial College London, which aims to provide a continuous and unobtrusive monitoring system for patients to capture transient, but life-threatening events. CodeBlue [34] was designed to operate across a wide range of devices, including low-power motes, PDAs and PCs, and it addresses the special robustness and security requirements of medical care settings.
In ubiquitous healthcare applications, the most significant limitations of wireless networks are slow data transfer rates and lack of a single connectivity standard that enables devices to communicate with one another and to exchange data. Other limitations include wireless devices that are still in their infancy and therefore slower in speed than desktop computers, high initial costs involved in setting up wireless systems and lack of real-time connectivity due to device mobility. Typical IEEE 802.15.4-based sensor network protocols have a non-IP network layer protocol in some limited area, where the TCP/IP protocol is not used. However, future applications of WSN consist of thousands of nodes, and IP-based networks may be connected to other networks via the internet [22]. This requires the use of an effective addressing mechanism needed for communication between the individual nodes in a WSN. One such mechanism is offered by the IPv6 standard. Thus, the emergence of 6LoWPAN can be treated as the beginning of a new generation of M2M networks.

2.2 IPv6 over LoWPAN (6LoWPAN)

The IETF working group was officially organized in 2005 to define data transmission in 6LoWPAN. Note that even though IEEE 802.15.4 devices are being considered for internet connectivity, the IPv6 technique has already emerged as a more powerful candidate for cheap, low-power microcontrollers and low-power wireless radio technologies in futuristic networks. The vast majority of simple embedded devices still make use of 8-bit and 16-bit microcontrollers with very limited memory, as they are low-power, small and cheap. At the same time, the physical trade-offs of wireless technology have resulted in short-range, low-power wireless radios with limited data rates, frame sizes and duty cycles. Released in 2003, the IEEE 802.15.4 standard was the biggest factor leading to 6LoWPAN standardization. The popularity of this new standard gave the internet community much needed encouragement to standardize an IP adaptation for wireless embedded links.

This section discusses the characteristics of 6LoWPAN and examines 6LoWPANs in terms of protocol stacks. 6LoWPAN is used for transmission of IPv6 packets based on the IEEE 802.15.4 communication protocol and IPv6 [35–39]. Designed to replace IPv4, the IPv6 protocol offers scalability for decades to come. In essence, the IPv6 technique expands the IP address space from 32 to 128 bits to overcome the older standard’s address-space limitation. Moreover, IPv6 increases the maximum transmission unit (MTU) from 576 to 1,280 bytes, in
response to the large link bandwidth size required for transmission. Implemented on top of the IEEE 802.15.4 layer, the 6LoWPAN protocol stack transmits packets using a higher-level protocol, thus increasing flexibility. Fig. 1 shows the characteristics of the 6LoWPAN protocol stack with three general parts: an M2M node, an M2M gateway and an IP network host. In order for 6LoWPAN to work with an IP network, the 6LoWPAN protocol stack supports a number of features, such as compression, fragmentation and mesh addressing of packet headers. Also, the 6LoWPAN protocol stack contains an additional interface for supporting communication based on the user datagram protocol (UDP) from gateway to server over the internet. Health parameter-related information is carried in the adaptation layer, required by and defined in the 6LoWPAN protocol stack.

![Fig. 1. Characteristics of the 6LoWPAN protocol stack [11, published with the permission of American Scientific Publishers].](image)

Fig. 2 shows the adaptation layer in 6LoWPAN. An adaptation mechanism allows interoperability between the IPv6 domain and the IEEE 802.15.4 protocol and enables header compression along with fragmentation and mesh addressing features. Significantly, the adaptation layer offers new functionality by allowing new packet formats. RFC 4919 and RFC 4944 propose an adaptation layer to allow the transmission of IPv6 datagrams over IEEE 802.15.4 networks [40–41].

A key concept applied throughout the 6LoWPAN adaptation layer is that it uses stateless compression to omit the header fields of the adaptation layer, network layer and transport layer. Common values occur due to frequent use of a subset of IPv6 functionality, such as UDP, TCP and internet control message protocol version 6 (ICMPv6). Health parameter data is added in the adaptation layer,
which is required by the 6LoWPAN stack. This stack supports many features, including the compression, fragmentation and mesh addressing of packet headers. In IP-enabled networks, IPv6 packets flow via the IEEE 802.15.4 protocol and various layers. The IEEE 802.15.4 frame format consists of a preamble, start of frame, frame length and address field. The adaptation layer handles routing packets and compression of IPv6 headers. 6LoWPAN represents an efficient extension of IPv6 into the wireless embedded domain, enabling end-to-end IP networking and features for a wide range of embedded applications. [Paper II]

![Fig. 2. Adaptation layer in 6LoWPAN [II, published with the permission of American Scientific Publishers].](image)

There is a huge range of applications that could utilize an approach based on embedded wireless internet connectivity. Today, these applications are implemented using a variety of proprietary technologies, which are difficult to integrate into larger networks or internet-based services. Among the benefits of using IP in these applications, thereby integrating them into the IoT are the following:

1. IP-based devices can be easily connected to other IP-enabled networks without the need for translation gateways or proxies.
2. IP networks allow the use of existing network infrastructures.
3. IP-based technologies have existed for decades, are very well known and have been proven to work and scale. The socket application programming interface (API) is one of the best-known and widely used APIs in the world.
4. IP technology is specified in an open and free way, with standard processes and documents available to anyone. As a result, IP technology encourages innovation and is better understood by a greater number of users.

Until now, only powerful embedded devices and networks have been able to participate natively in the internet. Direct communication with traditional IP networks demands many IPs, often requiring an operating system to deal with the attendant complexity and maintainability. Further, traditional IP sets high demands for embedded devices in terms of security, web services, management and frame size. These requirements have in practice limited the IoT to devices with a powerful processor, an operating system with a full TCP/IP stack and an IP-capable communication link. Typical embedded internet devices today include industrial devices with Ethernet interfaces, M2M gateways with cellular modems and advanced smartphones. A large majority of embedded applications involve limited devices, with low-power wireless and wired network communications. Aspects of wireless embedded devices and networks that are particularly challenging for IP include power, duty-cycle, multicast, mesh topologies, bandwidth, frame size and reliability.

Recently, many researchers are focusing on IP-related issues: the WirelessHART communication standard [42], released in September 2009, includes 6LoWPAN technology and, in 2008, the International Society of Automation (ISA) began standardization of a wireless industrial automation system called SP100.11a (also known as the ISA100.11a network layer) [43], which is based on the 6LoWPAN standard, providing IPv6 connectivity to all wireless field devices. In addition, the IP minimization technique with low-power microcontrollers and wireless technologies includes the µIP project [44] from the Swedish Institute of Computer Science, as well as the NanoIP project [45] to implement an alternative networking stack for control, automation and sensor networks from the Centre for Wireless Communications. In addition, the IP for Smart Objects (IPSO) Alliance was founded in 2008 to promote the use of the IP500 Alliance [46], which is working to develop a recommendation for 6LoWPAN communications. Several European projects specialize in future internet (FI) research, for example, the EU 4WARD project [47], in cooperation with the European Future Internet Assembly (FIA). Although most of the research related to FI does not consider embedded devices and networks, this aspect is
starting to gain interest. The EU SENSEI project [48], for example, specializes in making wireless sensor and embedded networks a part of the global internet, both current and future. One of the subjects of the project is how wireless embedded networks and 6LoWPAN-type functionality can be made an integral part of the FI. Many studies are being conducted in various industrial segments, such as transportation and automotive, smart home, environmental monitoring and building management either to improve business performance and functionality or to introduce new services. However, most of these projects are not related to healthcare applications.

2.3 Android mobile technology

Rapid technological development, ease of use and falling costs have made mobile devices increasingly popular, producing great changes in today’s lifestyle. During the past decade, the development of wireless mobile and information technologies (IT) has helped to extend the concept of ubiquitous coverage to new segments of society. Thus, many applications that were initially available at a fixed location only have been transformed into ubiquitous applications, to be used wirelessly and flexibly at anytime, anywhere. The same trend has been observed in the medical field. Over the years, many telemedicine and healthcare related societies and authorities have turned to wireless technologies to overcome the poor mobility of desktop PC-based healthcare monitoring systems. As a result, the possibility to monitor biomedical signals using a mobile device is no longer an unachievable dream.

In this work, an Android-based smartphone is used as monitoring terminal due to its smart functions and computer-like features. Compared to other smartphone operation systems, the Android device has many advantages, such as openness. Moreover, all applications are equal, there are no boundaries between applications and its development is fast. Furthermore, the Android smartphone is currently one of the most popular smartphones on the market.

Android, provided by Google and the Open Handset Alliance (OHA) [49–50], is an open-source software stack for mobile devices that includes an operating system, middleware and key applications. OHA is a group of approximately 78 technology and mobile companies, which combine their efforts toward the goal of accelerating innovations in mobile networks and toward offering a better mobile experience to the customer. Android is built on an open Linux kernel that includes such core system services as security, memory management, process management,
network stack and drivers. Further, the kernel acts as an abstraction layer between hardware and the software stack and can be extended to incorporate new cutting edge technologies. Using a Linux kernel as a hardware abstraction layer, allows Android to be ported to a wide variety of platforms.

Eclipse is a multi-language software development environment comprising an integrated development environment (IDE) and an extensible plug-in system. For the development of applications, a software development kit (SDK) is provided with the necessary tools and API. Eclipse SDK is meant for Java developers, who can extend its abilities by installing plug-ins written for the Eclipse platform, such as development toolkits for other programming languages, as well as create their own plug-in modules. All applications are written in the Java programming language. The application layer includes a set of core applications preinstalled on every Android device, including email, maps, contacts, web browser, phone dialler, calendar, text message and Android Market. Further, Android applications can utilize the functionalities of other applications and services. A service is an application component without a user interface that runs in the background for an indefinite period of time [51].
3 Machine-to-machine (M2M) technology

3.1 M2M communications

M2M is presently a major subset of the Internet of Things (IoT) concept [52–53]. This decade is widely predicted to see a rise in M2M communication over wired and wireless links. The origin of M2M communication is cloudy; it is not easy to exactly determine when cellular technology first began to learn to connect directly to other computer systems. As it is, due to the limitations of wired communication infra-structure, such as the presence of wires and inflexibility in network deployment, wireless networking systems are now considered as a solution for M2M technology. Typically, the M2M device class is characterized by very low-power consumption and little or no human intervention. In many cases, they autonomously communicate with each other or with a central controller. Particular focus is paid to the power requirements of M2M devices as well as the complications that arise when communicating between local networks and across the internet.

With the dramatic proliferation of embedded devices, M2M communication has become the dominant communication paradigm in many applications which concentrate on data exchange among networked machines, applications and services [54–55]. Examples of embedded devices and systems using IP today arrange from mobile phones, personal health devices, home automation, industrial automation and smart metering to environmental monitoring systems. This will lead to an unprecedented increase in data traffic involving machines communicating with other machines without human interaction.

For instance, researchers predict that by 2015 there will be 25 billion wirelessly connected devices – about three connected devices per person – that do not require any human intervention. Looking to the future, Cisco Inc. predicts there will be 50 billion devices connected to the internet by 2020 [56]. It is important to note that these estimates do not take into account rapid advances in internet or device technology; the numbers presented are based on what is known to be true today. Additionally, the number of connected devices per person may seem low. This is because the calculation is based on the entire world population, much of which is not yet connected to the internet. By reducing the population sample to people actually connected to the internet, the number of connected devices per person rises dramatically. For example, we know that approximately 2
billion people use the internet today. Insert these figures into the equation and the number of connected devices per person jumps to 6.58 in 2020.

Early work on a wireless M2M system with global network connectivity includes the effort of the European Telecommunication Standards Institute (ETSI), which set up a working group in 2009 for standardizing M2M, including an end-to-end IP architecture compatible with 6LoWPAN [57]. Another important initiative is the advanced metering infrastructure of the smart grid, which offers the greatest growth potential for systems requiring no human intervention, and is designed for characterizing power requirements and energy distribution. A possible solution to improving the scalability of smart grid communications has also been presented [58]. EISLAB at the Lulea University of Technology, Sweden, has introduced an information architecture based on service-oriented architecture (SOA) for future collaborative cloud-based automation systems. This architecture offers several useful features, such as real-time management, distributed event management and service specifications [59]. This system provides interoperable network services to complex and potentially very large multi-disciplinary, heterogeneous, networked distributed systems. Research along these lines serves to present a coherent view of the necessary architecture, taking account of technical specifications and other considerations and defining preliminary services.

M2M technology is evolving into a high-performance, high-efficiency, high-profit method used to monitor and control user assets, machinery and production processes, among others, while offering benefits such as increased reliability and cost savings. The unlimited potential of wireless M2M systems means that the market will be ready to experience explosive growth over the next few years. It is evident that the biggest challenges to M2M include remote management of M2M devices and data transmission in the absence of direct human-machine interaction. Considering the large number of M2M systems expected to be deployed in highly distributed networks and the requirement for low-cost devices and implementations, a global implementation of healthcare monitoring systems will soon be feasible and practical.

3.2 Mobile-based M2M healthcare system

Mobile communication devices can now provide efficient and convenient services, such as remote information interchange and resource access through mobile devices, allowing users to work ubiquitously. With the astronomical growth of the
cell phone ownership rate, mobile healthcare supported by mobile and wireless technologies emerges as a cost-effective care solution with a better overall health outcome. A feasible mobile device for ubiquitous healthcare must be cheap to produce, ultra-compact, lightweight and its power consumption must be low. In addition to broad communication capabilities, it must support such functions as health condition monitoring and display of biomedical signals. It is now possible to draw inferences in real-time from a range of behavioural data made available via mobile phones. Feedback can then be offered relating to these behaviours, enabling people to make better everyday lifestyle choices and, ultimately, to better manage their health [60–62].

6LoWPAN was introduced to enable the creation of a global IP-based M2M network, potentially involving trillions of devices. Such a network enables the implementation of healthcare applications with direct exchange of information between machines and the option of controlling devices without human assistance. Fig. 3 shows a block diagram of a personal M2M healthcare system for health condition monitoring in a global environment enabled by the flexibility and scalability of 6LoWPAN and mobile communication [Paper VII].

Fig. 3. Block diagram of overall system architecture [VII, published with the permission of IEEE].

3.2.1 System architecture

Shown in Fig 4 is the overall architecture of the proposed personal M2M healthcare system used to monitor patient health states. Utilizing 6LoWPAN and mobile communication, the system offers excellent flexibility and scalability. For global network communication, 6LoWPAN is connected to external IP-enabled networks by M2M gateways. In its typical role, a 6LoWPAN network operates on the edge of the system, acting as a stub network. For practical measurements, an M2M node, with integrated health sensors, collects and sends biomedical signals. This M2M node consists of a micro controller unit (MCU), radio frequency (RF)
transceiver chip and battery and transfers the measured biomedical signals to an M2M gateway connected to the internet. At the server, a server program monitors and analyzes the transmitted biomedical signals and network topologies. Then, the program verifies the recorded sensing values and analysis results, combining them with relevant personal data before sending this information to an Android mobile for user access within any internet supported area. [Paper VII]

**Fig. 4. System architecture of a personal M2M healthcare solution [VII, published with the permission of IEEE].**

### 3.2.2 Benefits of M2M networks

Among valuable concepts worth considering in relation to an M2M-based personalized healthcare system are flexible operation, integration, interoperability and interference, use of existing infrastructure, functionality, cost and government mandates. Table 1 summarizes a comparison of an M2M system and a conventional system to indicate the range and significance of the advantages offered by M2M. The integration of mobile-based M2M networks in healthcare applications will improve the quality and efficiency of treatment in various ways. The system presented here assumes that 6LoWPAN-based M2M systems will be used in the general hospital, office and home environments while patients move within these facilities. In addition, when patients move outside 6LoWPAN facilities, mobile services, provided by a mobile network or the internet, kick in to support health monitoring. Various potential applications for patient monitoring,
and benefits, such as measurement quality improvement, error reduction, record accuracy, cost reduction and location accuracy will be significantly improved by these technologies.

Table 1. Comparison of an M2M system and a conventional system.

<table>
<thead>
<tr>
<th></th>
<th>Conventional System</th>
<th>M2M-based System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexible Capacity</td>
<td>Fixed capacity for pollution facilities</td>
<td>Flexible capacity for pollution facilities</td>
</tr>
<tr>
<td></td>
<td>Difficult to vary and rearrange facilities</td>
<td>Easy to vary and rearrange facilities</td>
</tr>
<tr>
<td>Operation and Cost</td>
<td>Fixed-type operation</td>
<td>Variable operation: Rapid response to the size of pollution</td>
</tr>
<tr>
<td></td>
<td>Low efficiency and high expenses</td>
<td>High efficiency and low expenses</td>
</tr>
<tr>
<td>Efficiency</td>
<td>Fixed-type capturing ability: Difficult to link with production line</td>
<td>High-efficient linking with production line</td>
</tr>
<tr>
<td></td>
<td>Manual capture system: Low efficiency</td>
<td>Flexible capture system using wired/wireless integrated system: High efficiency</td>
</tr>
</tbody>
</table>
4 System design and implementation

This chapter describes the backbone of the proposed personal healthcare system, comprising several modules and programming techniques for M2M devices for wireless communication. Also the implementation of the overall system will be discussed. Essential modules are the ECG sensor, PPG sensor, M2M node, M2M gateway and smartphone device. Each module serves its own purpose, while at the same time collaborating with other modules to ensure the integrity and reliability of the whole system structure through such programming techniques as TinyOS programming, gateway tunnelling and server programming. The aim of this work is to set up a fully-integrated wearable system, able to acquire health data globally. Biomedical signals are measured utilizing 6LoWPAN and recorded data are first transmitted through an M2M gateway to a server PC for analysis. Analyzed health data are then sent to the smartphone device. Thus implemented, the proposed personal M2M healthcare system can be globally applied to improve accessibility via flexible networks and to enhance scalability using multiple M2M gateways connected to comfortable wearable sensors.

4.1 Hardware design

Core hardware of this system comprises the modules, i.e., the ECG sensor, PPG sensor, M2M node and M2M gateway. For low-power operation, the wearable sensors and M2M nodes used in the system maximize their lifetime by the use of a 3 V battery with a power consumption of less than 50 mW.

4.1.1 Health sensors

Generally, biomedical signals are ideal for predicting and monitoring patient health conditions. In the proposed system, two biomedical signals, ECG and PPG, form the basis for diagnostic analysis. Briefly put, ECG signals are recorded as electrical activity of the heart over time, while PPG signals are measured as changes in light absorption to monitor blood volumes within peripheral skin tissue. Wearable health sensors, shown in Fig. 5 and Table 2, were designed to enable the measurement of biomedical signals.
The PPG sensor was designed to obtain PPG waveforms and oxygen saturation data from the patient’s finger by calculating the ratio of red and infrared light on the device surface, which varies depending on how much light is absorbed by tissue. [Paper III] This PPG sensor contains analog signal processing, amplifiers, filters and analog-to-digital converters (ADC). Since raw signals are small and distorted, signal processing is initially determined by the communication system. Raw signals demand a 24 Hz low-pass filter (LPF) to reduce high frequency noise and a 0.5 to 10 Hz band-pass filter (BPF) to prevent the direct current (DC) component from enhancing the alternating current (AC) component. Filtered signals are fed into the MCU of the M2M node through a universal asynchronous receiver/transmitter (UART) port containing the sampled PPG signals at 75 Hz [63].

Attached to a T-shirt, the ECG sensor employs conductive fabric electrodes. Two of these, measuring 8 cm in size, are on the inside of the shirt over the chest area to enable skin contact. ECG signals from both chest electrodes are obtained by an analog signal conditioning circuit, which contains amplifiers as well as a low-pass and a high-pass filter (HPF) circuit. Next, raw signals are filtered and amplified through an analog signal conditioning circuit. The LPF and HPF
circuits are designed to eliminate analog noise signals with a high SNR. The final cut-off frequency is from 0.5 Hz to 34 Hz and total gain is 500 (27 dB). [Paper IV]

<table>
<thead>
<tr>
<th>Specifications of the health sensors.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Specifications</strong></td>
</tr>
<tr>
<td><strong>ECG Sensor</strong></td>
</tr>
<tr>
<td>Electrodes</td>
</tr>
<tr>
<td>Gain</td>
</tr>
<tr>
<td>Cut-off Frequency</td>
</tr>
<tr>
<td>Power</td>
</tr>
<tr>
<td><strong>PPG Sensor</strong></td>
</tr>
<tr>
<td>LED</td>
</tr>
<tr>
<td>Gain</td>
</tr>
<tr>
<td>Cut-off Frequency</td>
</tr>
<tr>
<td>Power</td>
</tr>
</tbody>
</table>

### 4.1.2 M2M devices

As shown in Table 3, the M2M devices of the personal healthcare system are designed to measure and transmit biomedical signals to a flexible and scalable M2M network. M2M nodes connected to health sensors are placed on the patient’s body and are mainly responsible for collecting and transmitting signals sampled at 100 Hz for ECG and at 75 Hz for PPG to the M2M gateway. Also the M2M nodes connected to wearable sensors are placed on the patient’s body. They are used to collect such health parameters as ECG signals, PPG signals and oxygen saturation values, which they then transmit to a server for monitoring and analysis. All M2M nodes come with their own unique IP address that is connected to the M2M gateway. Each of these nodes consists of a very-low power microcontroller, external memory and a transceiver unit packed in a small board. The M2M gateway forms a link between two different networks, one running IPv6 over IEEE 802.15.4, while the other is an IP-based network.

Moreover, the M2M gateway performs global address translation to either short 16-bit addresses or to 64-bit IEEE extended unique identifier (EUI) MAC addresses. TinyOS-based M2M nodes are allocated their own IP addresses by the M2M gateway to enable the transmission of IPv6 packets. The 6LoWPAN protocol stack manages this transmission of packets using the 6LoWPAN ad hoc on-demand distance vector (LOAD) routing protocols developed by the IETF.
group. This routing protocol guarantees flexibility in the face of topology changes in WSNs. [Paper V]

Table 3. Specifications of M2M devices [V, modified by author with the permission of American Scientific Publishers].

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>M2M Node</strong></td>
<td></td>
</tr>
<tr>
<td>MCU</td>
<td>MSP430 (16-bit RISC)</td>
</tr>
<tr>
<td>OS</td>
<td>TinyOS-1.x/2.0 (nesC)</td>
</tr>
<tr>
<td>RF Interface</td>
<td>IEEE 802.15.4</td>
</tr>
<tr>
<td>RF Controller</td>
<td>TI CC2420</td>
</tr>
<tr>
<td>Data Rate</td>
<td>250 Kbps</td>
</tr>
<tr>
<td>Power</td>
<td>AC 220 V-DC 3 V</td>
</tr>
<tr>
<td><strong>M2M Gateway</strong></td>
<td></td>
</tr>
<tr>
<td>CPU</td>
<td>S3C2410 (ARM9 Core)</td>
</tr>
<tr>
<td>OS</td>
<td>Embedded Linux</td>
</tr>
<tr>
<td>Network Interface</td>
<td>802.3 10 Mbps 1 Port, 802.11 b/g Wireless LAN 1 Port</td>
</tr>
<tr>
<td>RF Controller</td>
<td>TI CC2420</td>
</tr>
<tr>
<td>I/O Interface</td>
<td>RS-232 4 Port, USB2.0 2 Port</td>
</tr>
<tr>
<td>Protocol Stack</td>
<td>IPv6 Core Protocol, IPv4/IPv6 Dual Stack</td>
</tr>
<tr>
<td>Power</td>
<td>DC 5 V</td>
</tr>
</tbody>
</table>

4.1.3 **Android mobile device**

After emulator testing, the server program sends received data wirelessly to the patient’s Android mobile device. Various algorithms are combined into mobile application software created with the Java Android language to handle all server processes. Query processes handle communication between the server and the Android mobile device for a graphic real-time display of biomedical signals on the screen. The mobile monitoring program was implemented and tested on an Android mobile phone (Samsung Galaxy S, Korea) [64] running a 1 GHz ARM processor (Cortex A8, Hummingbird) and Android operating system (OS) version 2.3.6. Through wired or wireless internet connections, the server connected to different types of mobile devices and performed a range of development tests on them.
4.2 Software design

In terms of architecture, software for the personal M2M healthcare system falls into three parts: TinyOS programming in the M2M nodes, tunnelling processes in the M2M gateway for network access and server application program. These parts will be discussed in the following sections.

4.2.1 TinyOS programming

The proposed M2M nodes run on TinyOS, an open source operating system mainly for wireless embedded sensors, which was developed by the University of California, Berkeley, in co-operation with Intel Research. TinyOS performs services and procedures using a set of configured library components and custom-made components, designed to minimize the utilization of resources by the TinyOS kernel scheduler [65]. For TinyOS programming, TinyOS 2.x version is used to enable device identification (ID) based on unique IPv6 addresses (IPv4/IPv6 dual) using Kubuntu (Canonical Ltd., UK) or Cygwin (Cygnum Solutions, USA) which is a Windows-based Linux operating system [66]. Kubuntu is an operating system built by a worldwide team of expert developers, and it is used for TinyOS programming in this dissertation.

All M2M nodes are programmed with total 42,774 bytes of compiling size on M2M node’s memory to collect measured biomedical signals and create data packets for wireless communication. As shown in Fig. 6, all packets transmitted through the internet are verified by the server monitoring program, which receives the signals in 100-byte packets through the M2M gateway using Tera Term (terminal emulator). On receiving these packets, the monitoring program stores the recorded health data values in a database and dynamically plots the measured biomedical signals.
4.2.2 Gateway tunnelling

By enabling the use of the IPv6 technique, 6LoWPAN provides an extension to IP-based sensor networks. This serves to enhance the coverage area of such applications as the personal healthcare application presented here. The application’s M2M gateway provides reliable IPv6 communication for transmitting biomedical signals to a doctor or server via the internet. Utilizing IPv6 over the IEEE 802.15.4 represents a special match of the two technologies. As each M2M node is assigned a unique IPv6 address, they can directly communicate with each other, offering higher accessibility and an epoch-making network extension.

For IPv6 communication, each IPv6 address must be defined at the M2M gateway and server PC. As IP networks can usually be accessed by IPv4 addresses, the IPv6 to IPv4 tunneling process, which changes IPv4 addresses to IPv6 addresses at the M2M gateway, is required to access the server PC through the internet. In an experiment illustrated in Table 4, an IPv6 address, in this case, 2002:cbfa:79cf::cbfa:79cf, derived from the corresponding IPv4 address 203.250.121.207 (Pukyong National University, Korea) by the IPv6 to IPv4...
tunnelling process, is assigned to a register in the server PC. Also the M2M gateway is assigned an IPv6 address, namely, 2002:82e7:3b66:1::1, corresponding to the IPv4 address of 130.231.59.102 (University of Oulu, Finland). This is necessary, because each individual M2M node must be given a lower prefix address, such as 2002:82e7:3b66:100:22:ff:fe00:5 in 6LoWPAN by the auto-configuration function, as shown in Table 4. [Paper VI]

Table 4. Assignment of IP addresses [VI, published with the permission of IMCS 2012].

<table>
<thead>
<tr>
<th>Items</th>
<th>Assigned IP Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>M2M Gateway</td>
<td>IPv4: 130.231.59.102 (Finland) IPv6: 2002:82e7:3b66::1</td>
</tr>
<tr>
<td>M2M Node</td>
<td>IPv6: 2002:82e7:3b66:100:22:ff:fe00:5 Prefix IPv6: 22:ff:fe00:0 (to ff)</td>
</tr>
</tbody>
</table>

4.2.3 Server program

Measured biomedical signals are sent through the internet by the M2M gateway to the server PC for further processing. A monitoring and analysis graphical user interface (GUI) was designed with the C# language to monitor, store and process the received data, as shown in Fig. 7. On receiving a data packet through the M2M devices, the monitoring programme processes it, extracting useful data, as illustrated in Fig. 8. On reception, the sender’s IPv6 address is identified to ensure that the aggregated data is from the correct M2M device source. Then, the received data are scanned to ensure that the data packet is complete. This monitoring program performs its function continuously, monitoring not only biomedical signals, such as PPG signals and oxygen saturation data acquired by the wearable health sensors, but also information about the M2M devices, including current communication settings and IPv6 addresses in real-time. All packets transmitted through the internet are verified by the server monitoring program. It performs an accurate recognition process even if the patient is unconscious.
Fig. 7. Screen capture of the monitoring program on the server [VII, published with the permission of IEEE].

Fig. 8. Flowchart of the data process on the server [VII, published with the permission of IEEE].
Having received all transmitted packets via UDP communication, the monitoring program stores the values of the measured biomedical signals in a database and plots them dynamically. This monitoring program also displays the recorded values along with other relevant information, such as ECG and PPG waveforms, heart rate and the IPv6 addresses of the M2M node, M2M gateway and server IP. In addition, it queries the user to press buttons to initiate or end monitoring activities. Moreover, it has the capacity to provide good accessibility to a client PC with an IPv4 address. Thus, any internet-connected client, such as a desktop, laptop or tablet PC, or a mobile device, can access the measurement data, provided that they have a fixed IPv4 address. [Paper VII]
5 Results and performance analysis

5.1 Experimental setup

Practical tests were conducted to observe the performance of the personal M2M healthcare system and to evaluate its measurement and analysis methods. To that end, the designed hardware and software were subjected to experimental testing involving a global area network. Ten test subjects without heart disease were recruited for short-term tests lasting three minutes and long-term tests lasting 30 minutes. They were asked to overwork and exert themselves to the point that they were physically stressed. Their physical responses were measured in real-time using PPG and ECG sensors connected to M2M nodes. Each M2M node was connected to the wearable health shirt which recorded biomedical signals from sensors placed on their bodies and further transferred the thus collected data to the M2M gateway. Acting as the medium between the internet and 6LoWPAN networks, the M2M gateway delivered packets containing the measured biomedical signals using UDP communication.

The experimental setup was based on an international scenario involving the University of Oulu in Finland and Pukyong National University in Korea. One 6LoWPAN test environment at the University of Oulu was set to measure ECG signals. These signals were sampled at 100 Hz using embedded ECG sensors and saved in buffers in 20-byte packets for wireless communication. A second 6LoWPAN test environment was set up in another location at the University of Oulu to measure PPG signals sampled at 75 Hz. The PPG sensor performed data acquisition with a packet size of 5 bytes contained PPG signals, SpO2 and HR values. Both wearable sensors were placed so as to be compatible with the healthcare system on the subjects’ bodies. Each wearable sensor contained an M2M node with an IPv6 address for ID and high-gain ADC channels for high signal precision. The main function of the M2M nodes was to collect the measured biomedical signals from the wearable sensors and then forward the data to the server PC via the M2M gateway.

Positioned in Pukyong National University, Korea, the server PC was used to assess the test subjects’ health condition and to monitor the performance of wave-dependent data. Also information concerning 6LoWPAN networks was used to simulate real-time situations. Using IP addresses, the server PC can accurately determine position data, even if the person being measured is in an unconscious
state. This was done to in an attempt to create an environment that resembles the real situation at home, office or hospital, where patients may be stationary or moving about indoors or outdoors within direct or indirect range of a 6LoWPAN network. One scenario also covered the case when data from a number of patients have to be accessed at the same time.

<table>
<thead>
<tr>
<th>6LoWPAN datagram</th>
</tr>
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<tbody>
<tr>
<td>IEEE 802.15.4 Header</td>
</tr>
<tr>
<td>PPG Signals</td>
</tr>
<tr>
<td>ECG Signals</td>
</tr>
</tbody>
</table>

Fig. 9. Structure of 6LoWPAN packets [V, published with the permission of American Scientific Publishers].

Fig. 9 shows the structure of 6LoWPAN packets. Apart from the packet header, these packets comprise a total 29 bytes. The first two bytes are the node ID, which is needed to distinguish each individual 6LoWPAN node. The next two bytes illustrate sensor type, with 0x0060 denoting a PPG sensor and 0x0061 an ECG sensor. The remaining 25 bytes are the payload biomedical data. [Paper V]

5.2 Analysis and evaluation of health condition

Heart rate variability (HRV) is usually calculated by analyzing a time series of beat-to-beat or normal-to-normal (NN) intervals from ECG signals. Alternatively, they can be derived from pulse wave signals measured by PPG [67–69]. Two major methods for the analysis of HRV signals are time domain analysis and frequency domain analysis [70–72]. In addition, HRV serves as an indicator of stress, since it is regulated predominantly by the autonomic nervous system (ANS), which regulates bodily functions without volition or consciousness. The ANS is affected by sympathetic and parasympathetic nervous systems: sympathetic nerves excite the heart, increasing heart rate, whereas parasympathetic nerves reduce it. By accurately measuring HRV, detected variations can be used to determine psychological and physiological stress on the body.
Time domain analysis allows the extraction of fairly unstable signals, which are indicative of how the body is always ready to respond to external stimuli. Time domain analysis of HRV signals enables us to detect stress, fatigue and drowsiness, based on conclusions drawn from the heart rate (HR) distribution graph, the standard deviation of the NN interval (SDNN), the root mean square of successive differences (RMSSD), the proportion derived by dividing NN50 by the total number of NN intervals (pNN50) and the stress index (SI). In experiments conducted during this research, HR distribution displayed a range of reactions between normal state and stress state, as seen in Fig. 10. Normally, HR distribution tends to be spread widely and evenly, a telling sign that the sympathetic and parasympathetic nervous system of ANS operate accurately. On the other hand, when a person experiences stress, HR distribution tends to spread narrowly and centrally. This indicates that the parasympathetic nervous system is working harder than the sympathetic nervous system.

![Fig. 10. Time-domain comparison of HR distribution analysis in the normal and stressed state.](image)

A correlation between SDNN and RMSSD data serves to verify the different pattern for a person in the normal state and in stress, as shown in Fig. 11. Both the SDNN and RMSSD factor is found from the mean value for SDNN (45.7 ms) and RMSSD (39.8 ms) in the normal state under resting condition. On the other hand, in a state of stress, the SDNN and RMSSD factors exhibit clearly lower mean
values (34.1 ms and 24.4 ms, respectively) than in the normal state. These results, extracted from time domain analysis, are very interesting as they offer a way of interpreting a person’s health state.

![Graph comparing SDNN and RMSSD factors for time domain performance analysis.](image)

**Fig. 11.** Comparison of SDNN and RMSSD factors for time domain performance analysis.

As a parameter of the main method used in the histogram analysis, SI was employed to evaluate the state of autonomic regulatory mechanisms [73–74].

\[
SI = \frac{AM_0}{2 \Delta XM_0} \tag{1}
\]

The mode (M₀) represents the most frequent length of RR intervals and its amplitude (AM₀) corresponds to the maximum density of distribution at the maximum M₀. In essence, AM₀ is the percentage of RR intervals that equals the
The variation range ($\Delta X = \text{RR}_{\text{max}} - \text{RR}_{\text{min}}$) can be calculated using the distribution density function, and $\text{RR}_{\text{max}}$ and $\text{RR}_{\text{min}}$ can be found at a level of 2% of the AMO. SI characterizes the activity of the ANS and the extent of centralization in cardiac rhythm regulation. This parameter is sensitive to the strengthening of the tone of the sympathetic nervous system. The SI histogram serves as a reflection of the normal state of health of the body and provides some useful clues for medical diagnosis. Thus, the value of SI increased from 87.2 to 109.6 under stress, and there was a significant difference both graphically and statistically. Time domain analysis extracted fairly uniform and stable RR intervals in the stressed state reflecting activation of the parasympathetic nervous system. On the other hand, unstable RR intervals in the normal state tended to indicate that the body was always ready to respond to stimuli from the external world.

In frequency domain analysis focusing on negative emotions, such as stress, fatigue and drowsiness, power spectrum density (PSD) analysis provided basic information of power distribution as a function of frequency. Three main spectral components are required for spectrum power indicator analysis: very low frequency (VLF), low frequency (LF) and high frequency (HF) components. Measurement results obtained from PSD analysis for VLF, LF and HF power components are usually given in absolute values. Presence of LF and HF power components emphasizes the controlled and balanced behaviour of the two branches of the ANS. Absolute values of LF and HF power components describe the total power distribution of spectral components. It turned out that the mean values of HF and LF power components differed somewhat in the normal state and in stress, as shown in Fig. 12.
Based on these results, the ratio of LF/HF was used to provide a health state assessment in both normal state (R = 2.49) and in stress (R = 3.63). Table 5 summarizes the results of a comparison of the mean values of HRV characteristics in time and frequency domains. [Paper V, VI]
Table 5. Comparison of the mean values of HRV characteristics in time and frequency domains [V, VI, modified by author with the permission of American Scientific Publishers].

<table>
<thead>
<tr>
<th>Variables</th>
<th>Normal State</th>
<th>Stressed State</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time Domain Analysis</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HR (Times/s)</td>
<td>77.9 ± 1.12</td>
<td>73.8 ± 0.26</td>
</tr>
<tr>
<td>RR Interval (ms)</td>
<td>771.4 ± 20.7</td>
<td>813.2 ± 9.2</td>
</tr>
<tr>
<td>SDNN (ms)</td>
<td>45.7 ± 3.9</td>
<td>35.1 ± 2.7</td>
</tr>
<tr>
<td>RMSSD (ms)</td>
<td>39.8 ± 4.1</td>
<td>24.4 ± 2.7</td>
</tr>
<tr>
<td>pNN50 (%)</td>
<td>13.01 ± 3.60</td>
<td>7.33 ± 1.27</td>
</tr>
<tr>
<td>SI</td>
<td>87.2</td>
<td>109.6</td>
</tr>
<tr>
<td><strong>Frequency Domain Analysis</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LF (ms²)</td>
<td>619.54 ± 30.17</td>
<td>246.37 ± 14.28</td>
</tr>
<tr>
<td>HF (ms²)</td>
<td>248.43 ± 24.15</td>
<td>70.72 ± 19.43</td>
</tr>
<tr>
<td>Ratio of LF/HF</td>
<td>2.49 ± 0.23</td>
<td>3.63 ± 0.86</td>
</tr>
<tr>
<td>ln LF</td>
<td>6.43</td>
<td>5.51</td>
</tr>
<tr>
<td>ln HF</td>
<td>5.52</td>
<td>4.25</td>
</tr>
</tbody>
</table>

The evaluation of health condition was mainly conducted by processing the HRV analysis, which is a simple yet powerful analysis method in the time and frequency domain. The analysis results from the HRV analysis were used as an indicator of ANS activities to reveal negative emotions such as fatigue, stress, drowsiness, and so on. In addition, physiological processes were realized with the autonomic balance diagram methodologies for high reliability of the biomedical signal processing. Most important health conditions such as cardio-related diseases and physiological states can be evaluated by the proposed methodologies using the results of health parameters. Thus, health features were used to evaluate health condition by comparing overall health parameters in the normal and stressed states. Both states were indicated with significant difference to the values of health parameters. Detailed analysis of health conditions will be studied for the more accurate and precise healthcare services in the future.

### 5.3 Mobile healthcare service

Functionality of the mobile monitoring service was corroborated by a set of monitoring tests. These were carried out by running an Android emulator on the server, before installing it on the cellphone. The Android SDK provides emulators that can mimic a variety of Android versions, screen dimensions and phone behaviours. It runs a bit slower than a real phone, but provides efficient support...
for all features and lifecycle events, including persisting state, writing local files, etc. Android emulator tests were conducted on the monitoring application using the measured PPG signals, as shown in Fig. 13. After testing the monitoring application by the Android emulator, the monitoring application was installed on the Android mobile via a direct cable from a PC (could have been installed wirelessly from the Android Market store).

![Android Emulator Test]

For practical tests, a Samsung Galaxy S cellphone, based on the Android OS, was used to monitor biomedical signals, heart rate and blood oxygen saturation as well as the IPv6 address of the transmitting M2M node. Fig. 14 shows the designed monitoring application running on a Samsung Galaxy S mobile phone. This system samples PPG signals at the rate of 75 Hz, meaning that 15 data packets are sent within 1 second. As each data packet comprises 5 PPG data points, a total of 75 PPG data points are sent in a second. Thanks to the large screen, the waveform display on this monitoring application provides a good graphic visualization for the user wherever internet is properly supported. [Paper VII]
Fig. 14. Monitoring application on an Android mobile: (a) Start mode. (b) Monitoring mode. (c) Appearance of the Android mobile during monitoring [V, published with the permission of IEEE].
6 Discussion

This dissertation studied the design and implementation of a personal M2M healthcare system with wearable health sensors and M2M devices. Focus was on the establishment of a global M2M network, in which biomedical signals can be measured and monitored. Crucially, this internet-based network incorporates 6LoWPAN and mobile communication to expand its coverage area. Using several proposed global network scenarios, a series of practical tests were conducted for data measurement, transmission and analysis purposes, and an evaluative comparison of packet reception rates was conducted to acquire reliable quantitative information. In addition, performance of the personal healthcare system was investigated by comparing analysis results based on the proposed health parameters. Transmitted through the network, the extracted health parameter values were used as indicators of test subjects’ health condition to provide information on potential cardio-related diseases. To that end, their stress states were assessed and verified using features of ANS activation. To obtain reliable results, several health parameters were compared in normal state and in stress.

The rest of the chapter summarized open issues for future work that are relevant for the advancement and improvement of the proposed system to make it more reliable, practical and feasible. A central strand in research on healthcare monitoring involves the evolution of network integration and the management of embedded devices running multiple tasks simultaneously. This is a very promising field with an exponentially increasing number of M2M devices and opportunities in the marketplace that have the potential to significantly change the healthcare system and make it more efficient. Limitations do exist and further studies are mandatory to achieve better performance. Improvements and issues correlated to global M2M networks will be discussed below:

1. Hardware limitations: In order to make these wearable devices practical, a series of technical, legal and sociological obstacles need to be overcome. For example, these devices need to be non-intrusive, comfortable to wear, efficient in power consumption, preserve privacy and have a user-friendly interface. They would also need to have a very low failure rate and highly accurate alarm triggers, especially if used for diagnostic purposes. However, in any future healthcare system, the maintenance of health sensors and M2M nodes requires more powerful processing capability, larger memory space and longer battery life. Moreover, the battery life of sensor modules, traffic conditions in wireless
communication, system stability, portability and the necessary hardware installation method must not distract or trouble the system. So, further improvements can concentrate on designing optimized M2M devices for flexible utilization in global networks.

2. Network improvements: In this dissertation, practical tests involving global network use were conducted in an international environment for the measurement and analysis of biomedical signals. It turned out that relative performance is highly dependent on the IP-enabled network condition, not on the 6LoWPAN condition. Ways of improving the global network condition need to be studied to enhance the performance of the proposed system with such IP-based communication techniques as TCP/IP and UDP. In addition, to achieve reliability in a global network, firewall configurations and policies need to be considered to enable access to the host network.

3. Health features: A number of methodologies may be applied to assess an individual’s health condition, and the selection of health parameters is essential for good monitoring performance. This dissertation presented several analysis methodologies to health condition assessment based on processing physiological data, including HRV and ANS analysis. Stress in test subjects was assessed by comparing several health-related parameters in normal state and in stress. One issue of concern is communication traffic in wireless networks. Heavy traffic, further enhanced by the workload caused by M2M device processing, may bring down the entire system. Thus, to achieve a more reliable mobile healthcare system, a web-based database is required to manage individual patient information, including data from biomedical signal measurements. Text messages can also be sent by a warning system to other involved agencies and persons, such as parents or siblings, for acknowledgment.
Summary

This dissertation successfully implemented a personal M2M healthcare solution using Android mobile devices in global networks with the help of the IPv6 technique. Initially, motivation for the proposed system was discussed, followed by a description of design challenges. A mobile healthcare sensing method was hypothesized, including wearable health sensors for chronic or recovering patients to record changes in biomedical signals in an IP-enabled WSN. In addition, communication architecture for a personal M2M healthcare system relying on 6LoWPAN and mobile techniques was introduced as a way of increasing the coverage of the service. The proposed system presented key ideas for establishing a 6LoWPAN network that provides efficient support for IPv6 over the IEEE 802.15.4 protocol for healthcare applications.

Generally, biomedical signals are ideal for predicting and monitoring the health condition of a patient. In the proposed system, two biomedical signals, ECG and PPG, were dedicated to carrying out analysis methodologies. Briefly, the ECG signal produces a record of the electrical activity of the heart over time, while the PPG signal is the measurement of light absorption to monitor blood volume within peripheral skin tissue. Wearable health sensors and M2M devices were designed for the measurement of ECG and PPG signals and for the wireless transmission of measurement data to a server PC through IP-enabled internet. Thus, the proposed M2M healthcare system can be globally applied to improve accessibility via flexible networks and scalability by the use of multiple M2M gateways connected to comfortable wearable sensors.

Several methodologies were brought to bear on the analysis of biomedical signals to enable assessment of stress. Among the studied parameters were HR, HRV, SDNN, RMSSD, pNN50, and SI (time domain) as well as VLF, LF, HF, ratio of LF/HF, ln LF and ln HF (frequency domain). By monitoring the activation of ANS under different conditions, it was possible to identify when a person was in a state of stress, which was verified by a comparison with normal state. Results from HRV analysis were used as an indicator of ANS activity to reveal negative emotions, such as fatigue, stress and drowsiness. However, in this dissertation, identification of health conditions was limited to stress, as normal relaxed state provides a good basis for comparison. Thus, the assessment of health condition relied on comparing overall health parameters in normal state and stress state. Based on these results, both states showed significant differences in recorded parameter values.
The Android mobile healthcare application is easy to port to other mobile devices, such as smartphones, tablet PCs and laptops and is capable of real-time monitoring of biomedical signals. To access mobile healthcare services based on the Android mobile healthcare application within internet coverage, an Android mobile phone was selected. Thus, a Samsung Galaxy S model smartphone was used to monitor the 100 Hz ECG signal and 75 Hz PPG signal with the analyzed health features. The mobile healthcare system provided useful information on signal display, sensor type, data bytes, IPv6 address and health features. A state of stress produces a higher ratio of LF/HF in the ECG signal and a higher stress index in the PPG signal. Combining 6LoWPAN and mobile communication techniques allowed an extreme network connectivity extension offering a higher accessibility of M2M devices for seeking better achievements of user-oriented healthcare services with maximum mobility and flexibility to the patients who are in urgent need of such services. Harnessing a range of technologies makes it possible and feasible to create a more advanced mobile healthcare system through the use of existing infrastructures to assure the arranged research questions.
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Original Papers


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Original publications are not included in the electronic version of the dissertation.
462. Kukkola, Jarmo (2013) Gas sensors based on nanostructured tungsten oxides

463. Reiman, Arto (2013) Holistic work system design and management: — a participatory development approach to delivery truck drivers' work outside the cab

464. Tammela, Simo (2013) Enhancing migration and reproduction of salmonid fishes: method development and research using physical and numerical modelling

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Sang-Joong Jung

PERSONAL MACHINE-TO-MACHINE (M2M) HEALTHCARE SYSTEM WITH MOBILE DEVICE IN GLOBAL NETWORKS