CONTEXT-AWARE VERTICAL HANDOVER MECHANISMS FOR MOBILE PATIENT MONITORING

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Saraswati Salutations

या कुंदेंदु तुषारहार धवला, या शुभ्र वस्त्रावृता |
या वीणावर दण्डमंडितकरा, या श्वेतपद्मासना ||
या ब्रह्माच्युतशंकरप्रभृतिभिर्देवैः सदा वन्दिता |
सा मां पातु सरस्वती भगवती निःशेष जाड्यापहा ||

Saraswati (Sanskrit: सरस्वती) is known as the goddess of knowledge, music, arts, science and technology according to the ancient Indian culture.

Salutations to the supreme Goddess Saraswati - whose face is fair as a jasmine flower, luminescent like the moon and delicate as a snow flake; who is dressed in brilliant white garments. She holds the musical instrument in her hands to bestow boons to her disciples as she sits on her white lotus throne.

Abstract

This PhD thesis is a scientific output of author's work in a Dutch Government project titled FREEBAND AWARENESS[1] project. The AWARENESS project has contributed to the area of mobile computing and consumer electronics to enable a new generation of *context-aware applications*, one of them is *mobile patient monitoring*. The mobile patient monitoring refers to continuous or frequent measurement and analysis of biosignals of a mobile patient by employing mobile computing and wireless communication technologies. A typical mobile patient monitoring system consists of the following: a *sensor system* for capturing patient's biosignals (e.g. *ElectroCardioGram* - ECG), a *mobile base unit* (MBU) to facilitate storage, processing and transmission of biosignals, and a *back-end system* that obtains biosignals from the MBU and provides health-related services to the patient; e.g. dispatching ambulance to the patient's location in the case such a need arises. The sensor set and the MBU together comprise a *Body Area Network* (BAN). The communication between the MBU and the back-end system is referred as *extra-BAN communication*, and it requires availability of wireless Internet connectivity to the MBU. In the mobile patient monitoring cases considered in this thesis, it is necessary to continuously deliver patient's biosignals to the location of a healthcare professional in real-time. E.g. In a *remote physiotherapy treatment*, a patient may be performing exercises at home, while her biosignals are continuously sent to the site of physiotherapist using a mobile patient monitoring system. The mobile patient monitoring system used in this thesis is known as *MobiHealth Patient Monitoring System* (MHPMS).

In order to take an accurate decision about patient's health condition, the healthcare professionals have clinical requirements on the quantity and quality of biosignals received at the back-end system. In this thesis, we map these clinical requirements onto the *QoS requirements* of biosignals delivery. In a mobile patient monitoring system, it is necessary that the biosignals delivery QoS requirements are fulfilled by the (wireless) networks constituting an extra-BAN communication path. The consequence of not fulfilling these requirements may result in the loss of biosignals, additional delay in receiving biosignals and consequently an inability of a healthcare professional to take an accurate decision. Common problems observed during the real-life trials of mobile patient monitoring systems are the following: 1) Due to the patient mobility, the continuity of patient monitoring is affected as the wireless networks availability changes with the location; 2) Often, the extra-BAN communication QoS offered by currently deployed wireless networks is variable – specifically, it is dependent on location, time, wireless network technology and number of users simultaneously transmitting data and it is inadequate for the continuous mobile patient monitoring applications; and 3) The duration of a

[1] http://awareness.freeband.nl/

continuous patient monitoring session is restricted due to limited battery capacity of the MBU.

In the mobile computing domain, it is a standard practice to use a technique known as *vertical handover* to handle wireless network availability changes resulting from personal mobility and also for the QoS improvement. The term vertical handover refers to the switchover of a mobile device from one network connection to another for sending and receiving data. In case of the availability of multiple networks to switchover to, vertical handover techniques also provision algorithms to select the most suitable wireless network. Hence, in this thesis, we introduce and evaluate the use of context-aware vertical handover mechanisms to address the problems in the mobile patient monitoring domain. The specific research problem addressed in this thesis is as follows:

In the MHPMS, for the continuous mobile patient monitoring cases, how to use a vertical handover technique to satisfy QoS requirements of biosignals delivery in the environment characterized by patient's mobility, deployment of multiple wireless networks technologies, uneven geographic distribution of the wireless networks, variable QoS characteristics of the wireless networks and limited battery capacity of the MBU?

To address this problem, we studied literature related to the following areas: mobile patient monitoring, vertical handover and context-aware computing. Based on this study, we present two context-aware vertical handover mechanisms for use in the MHPMS. The vertical handover technique ensures that despite patient mobility, the MBU is always connected to one of the available wireless networks. The use of context-aware computing based architecture emphasizes modularity and composability of components responsible for the tasks of *context acquisition*, *context processing* and *context reasoning*. In the proposed context-aware vertical handover mechanisms, the components *context sources*, *context processor* and *context reasoner* are provisioned to aid the *handover decision making* process in which a suitable wireless network surrounding the MBU is chosen for delivering biosignals. Depending on the availability of context sources and their placement, we propose two vertical handover mechanisms namely the *mobile controlled vertical handover* (MCHO) mechanism and the *network assisted vertical handover* (NAHO) mechanism.

The performance evaluation of MCHO mechanism in an operational MHPMS test-bed demonstrates that the proposed mechanism addresses problem of patient mobility and provides higher extra-BAN communication QoS compared to the MHPMS which uses only WWAN network for the biosignals delivery.

Based on the experience with MCHO mechanism and developments in the area of *QoS predictions*, we propose the NAHO mechanism; wherein the context information is obtained from the context sources located on the MBU and fixed network. The QoS predictions context source is provisioned in the fixed network to provide following context information: *wireless networks availability* and *their application level QoS characteristics as a function of location*, *time*, and *wireless network technology*. In the NAHO mechanism, the QoS predictions are fetched on the MBU and processed continuously for taking a network selection decision according to the current network context, mobile device context and QoS requirements of biosignals delivery. Due to the unavailability of an operational QoS predictions context source, the NAHO mechanism is validated using an extensive set of simulations. The simulation results show that compared to the MCHO mechanism, the NAHO mechanism provides higher QoS for biosignals delivery at the cost of higher number of handovers. The simulation results also show that by using proposed NAHO mechanism, it is possible to achieve power savings on certain types of mobile devices used as MBU in a mobile patient monitoring system.

Based on the obtained experimental results, we conclude that the proposed mechanisms together address common problems observed in the trials of mobile patient monitoring systems. For the further research, we recommend that the M-Health research community pays particular attention to the QoS requirements elicitation of the mobile patient monitoring applications, since the QoS requirements of biosignals delivery are specific to the mobile patient monitoring application. Furthermore, the latest trials of mobile patient monitoring systems report that it is usual for the current mobile patient monitoring prototypes to suffer from unpredictable wireless connectivity and variable QoS problems. Hence we conclude that the upcoming mobile patient monitoring systems can benefit from the NAHO mechanism proposed herein if an accurate, reliable and operational QoS predictions service is put in place.

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The teacher (in Sanskrit - Guru) is of supreme importance in the Indian philosophy. A guru is one who is regarded as having great knowledge, wisdom, and authority in a certain area, and who uses it to guide others. For this reason, I am grateful to all my teachers from the following institutions: Indian Institute of Technology - Mumbai, Dr. Babasaheb Ambedkar Technological Univerisity, Lonere, Maharashtra, India and G. B. Vader Highschool, Pali, Raigad, India.

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I am proud to be associated with the University of Twente. I deeply acknowledge the learnings and well-funded research opportunities provided by CTIT – in terms of various technical events, symposiums, speeches and conferences. In addition, my stay in The Netherlands exceeded my own expectations. The people are warm, caring and realistic. I am happy that the decision made in February 2005 to take on the research opportunity in The Netherlands has been the most potent decision in my life.

Certainly, completing this thesis has been a demanding task that needed the best of me, and I am indebted to those who helped me to rediscover my inner abilities and keep my motivation high – even in the rough times of life. The list of people I acknowledge herewith is not at all exhaustive. Herewith, I thank to all of them whose names do not appear here, however, without whose support and guidance I would have not seen this day.

Pravin Amrut Pawar
Enschede, The Netherlands.
October 2011.

Contents

Chapter 1

Introduction

This PhD thesis is a scientific output of the author's work in the FREEBAND AWARENESS project[2]. The AWARENESS project exploited innovations in the area of mobile computing and consumer electronics to enable a new generation of context-aware applications [Wegd05]. In this project, a particular attention was paid to the applications in the *mobile health* domain. The AWARENESS applications in the mobile health domain acquire context information about mobile patients, healthcare professionals and computing and communication resources to assist a patient in day-to-day living and emergency situations. In this chapter, we present our motivation behind the reported research, specific research problem and thesis research objectives. This chapter is organized as follows: Section 1.1 presents background and motivation behind the reported research. Section 1.2 illustrates the research problem. Section 1.3 details on the research objectives which follow from the research problem. The thesis outline is presented in Section 1.4.

1.1 Background and Motivation

The *Information and Communication Technology*, prevalently referred to as ICT, has become an integrated part of our daily lives, to transform into another basic need of the mankind. The ICT is revolutionizing daily living, communication and behavior of people with applications in almost every area of life. Often, ICT is referred with respect to a particular domain in which it is applied, e.g. *ICT in education* or *ICT in healthcare*. ICT in healthcare is also known as the *electronic Health* (*E-Health)*. E-health is a rapidly growing field in the intersection of medical informatics, public health and business. E-Health refers to the health services and information delivered or enhanced through the Internet and related technologies [Eyse01].

The healthcare sector is a chain model, where every stakeholder is responsible to fulfill certain functionality. Due to the widespread adoption of mobile devices and

[2] http://awareness.freeband.nl/

ubiquitous availability of wireless networks, the healthcare services and information delivery are undergoing transition from the E-Health to the *Mobile Health* (*M-Health*). M-Health refers to the appliance of mobile computing, wireless communications and networked computing technologies to deliver or enhance diverse health services and information in which the patient has a freedom to be mobile, maybe within a limited geographic area. The *mobile patient monitoring* is one of the emerging M-Health applications. It refers to the continuous or frequent measurements and analysis of the biosignals of a possibly moving patient remotely by using the mobile computing, wireless communication and networked computing technologies.

1.1.1 Biosignals Processing Steps in the Mobile Health Systems

The term *biosignals* refers to various types of signals that quantify physiological processes of the living organisms. The common types of biosignals [Erme09] are: 1) measurable using physical quantities e.g. temperature or pressure; 2) measurable using electrical quantities e.g. *ElectroCardioGram* (ECG) and *Heart Rate Variability* (HRV); and 3) measurable using biochemical quantities e.g. *concentrations*. The healthcare professionals use biosignals for properly diagnosing a disease, making a treatment decision and providing feedback to the patient. To achieve these, the measured biosignals undergo certain processing steps [Töni07] as shown in Figure 1.1.

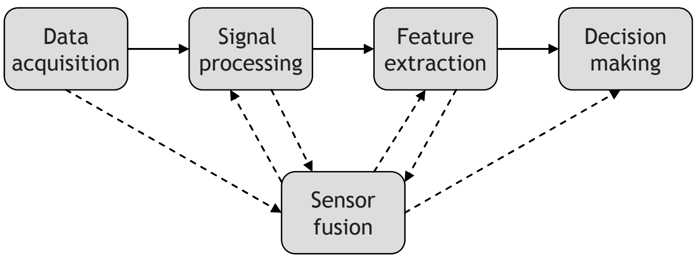

Figure 1.1: General steps in the biosignals processing

During the *data acquisition* step, the physiological sensors obtain patient's physiological data and convert it into electrical signals. The second step named *signal processing* consists of transformation, amplification, filtering and interpretation of biosignals (e.g. construction of an ECG using data obtained from the ECG electrodes). The information obtained during this step is further used for extracting *features/events* that indicate changes in biosignals that meet certain conditions (e.g. increased heart rate above a certain threshold). The data obtained from multiple sensors can possibly be combined to create a higher level health state description during the *sensor fusion* step. The sensor fusion step doesn't have a certain position in the biosignals processing chain [Töni07]. It may be performed at several levels, e.g.

raw data fusion and feature level fusion; or may not be performed at all. The final step in the biosignals processing chain is called *decision making*. In this step the decision of whether a condition for a particular type of health problem is met is taken. The output of this step may also be used to provide a feedback to the patient.

1.1.2 Mobile Patient Monitoring System

The term *mobile patient monitoring* refers to continuous or frequent biosignals measurements and analysis of a possibly moving patient remotely by means of mobile computing, wireless communication and networked computing technologies. The scientific literature reports a number of mobile patient monitoring systems. In this section, we present a generic architecture of mobile patient monitoring systems based on the literature studied from [Ango00, Gao07, Gay07, Halt04, Lin04, Sata00 and Wai08 and Jone09].

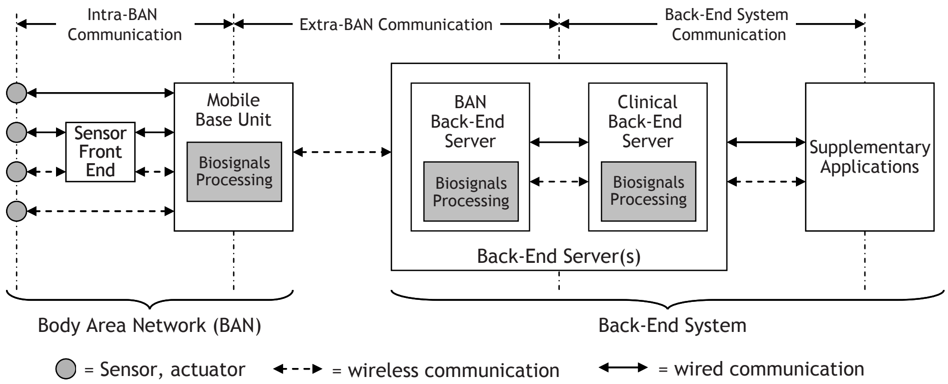

Figure 1.2: A generic architecture of mobile patient monitoring systems

As shown in Figure 1.2, a generic architecture of mobile patient monitoring systems is a set of the *body area network* (BAN) and the *back-end system* (BESys). The BAN consists of the *mobile base unit* (MBU) and other BAN devices [Jone09]. The communication within the BAN devices is referred as *intra-BAN communication*. The BAN devices are sensors, actuators and other devices used for clinical purposes. Depending on their position, the BAN devices are of two types: *invasive* and *non-invasive*. The invasive devices (e.g. sensors and actuators) are inserted in the living body by incision or by insertion of an instrument; while the non-invasive devices do not infiltrate patient's body and do not need any invasive medical procedure. The intra-BAN communication is supported by wired links, wireless links or a mixture of the two.

The sensors are used to acquire biosignals of a patient. These biosignals can be directly sent to the MBU or via the *sensor front-end* (SFE). The SFE may perform signal processing on the biosignals before sending them to the MBU. Further biosignals processing steps can be applied locally within the BAN. E.g., the patient monitoring system in the HEARTRONIC project [Roch08] provisions an *ECG pattern recognition module* on the MBU. This module detects irregular ECG patterns of patients suffering from coronary diseases. If needed, a MBU functions as a communication gateway for transmitting biosignals to the BESys. The communication between the BAN and the BESys is named as *extra-BAN communication*. In order to facilitate patient mobility, the extra-BAN communication must be supported by a wireless link. After the biosignals are received at the BESys, they may undergo further processing and storage. E.g., in the HEARTRONIC system [Roch08] whenever an irregular ECG pattern is detected on the MBU, the patient's location and ECG pattern activity are sent to the BESys. The BESys further alarms to the responsible healthcare professional.

The BESys comprises of the *back-end server(s)* and healthcare applications which make use of biosignals being received at these servers. E.g. After interpreting the biosignals, the healthcare application may provide emergency assistance to the patient by dispatching a medical team to the patient's location. The back-end servers are of two types: *BAN back-end server* and *clinical back-end server* [Jone09]. These two servers could be collocated with each other forming a single back-end server. The BAN back-end server is the server to which MBU transmits patient's biosignals. The clinical back-end server may host services (e.g. ECG viewing service) which make use of biosignals obtained from the BAN back-end server for further use by healthcare professionals. The communication within the elements of BESys is referred as the *back-end system communication*.

Continuous Delivery of Biosignals to the Back-End System

The biosignals processing steps shown in Figure 1.1 are mapped onto computing devices in a mobile patient monitoring system. These devices are sensor system, MBU, back-end server(s) and devices hosting healthcare applications. The mapping of biosignals processing steps onto these computing devices is not fixed and it is specific to the medical application purpose. For certain patient monitoring purposes a decision making step is mapped onto the BAN devices. E.g., in the *Myofeedback system* evaluated in [Veld08], a patient suffering from the neck and shoulder pain wears a BAN consisting of surface electromyography (SEMG) electrodes. These electrodes record biosignals activity of the upper trapezius muscles. In case these muscles are not relaxed enough, a patient immediately receives a local feedback in the form of vibration of a certain BAN device. The vibration is a feedback suggestion for the patient to relax. In the Myofeedback system, all the general steps of biosignals processing are implemented within the BAN.

There are possible reasons for mapping a decision making step onto the devices of the back-end system. E.g. in the *MobiHealth Patient Monitoring System* [Halt04] used for the trauma situations, the surgeon in the hospital takes a decision about the surgery on a trauma patient. In this system, a trauma patient wears a BAN consisting of the sensors which acquire respiration rate, ECG and pulse oximetry biosignals. While the on-site trauma team is transporting a patient to the hospital, the in-hospital trauma team monitors the condition of a patient using biosignals being received continuously at the back-end system in the hospital. We refer to these types of cases as the continuous biosignals delivery cases, since during the patient monitoring session the biosignals information is shared simultaneously among at least two participants – the patient and the healthcare professional.

QoS Requirements for the Continuous Biosignals Delivery Cases

For the decision making step, the healthcare professionals have requirements on the quantity, quality and time duration of biosignals being received at the back-end system. The quantity of biosignals sampled per second determines the bandwidth requirements of biosignals delivery. In the instances where certain action is expected from the patient, there is a temporal requirement on the in-time reception of the healthcare professional's feedback. E.g. in the remote physiotherapy treatment [Ferg09] case, a patient is required to perform certain physical movements while the physiotherapy session is in progress. For these cases the requirements of healthcare professionals need to be mapped onto the *Quality of Service* (QoS) requirements of biosignals delivery. As we illustrate in Chapter 4, the QoS parameters to be considered are *goodput*, *data loss ratio* and *round trip time*. In order for successful decision making and feedback, these QoS requirements need to be met by the extra-BAN communication path. The consequences of not meeting the QoS requirements are deficiency in the decision making process and not allowing the patient to benefit from the feedback.

Analysis of Existing Mobile Patient Monitoring Systems

For inferring the generic architecture shown in Figure 1.2, we studied individual mobile patient monitoring systems reported in [Ango00, Gao07, Gay07, Halt04, Lin04, Sata00 and Wai08]. A comparative study of these systems is presented in Chapter 4. The analysis of these mobile patient monitoring systems show the following merits. These systems have been used in both, the outdoors and indoors environments. The systems are user-friendly, convenient for both, the patients and healthcare professionals. The trials of these systems have shown feasibility and acceptance of these systems in a day-to-day life. During the trials, it is observed that the use of mobile patient monitoring systems help to reduce the response time of a treatment. A mobile patient monitoring system can be custom designed for treating a particular type of patient or it can be generic enough to cater for different classes of patients and even patients suffering from multiple co-morbidities.

The problems reported during the trials of these systems are as follows. The wireless network problems refer to the lack of sufficient bandwidth for biosignals transmission, high delay, wireless network coverage unavailability and plausible effect of weather conditions on the wireless signal quality. These problems result in a situation that the healthcare professionals do not have access to high quality biosignals data. Considering these aspects, the mobile patient monitoring systems need to incorporate mechanisms for making available high quality biosignals data to the back-end system.

Vertical Handover

The existing deployment of wireless network technologies can be classified into two categories [Bern04]: 1) *Wireless wide area network* (WWAN) technologies (e.g. GPRS) that provide low-bandwidth and high-latency service over a wide geographic area[3]; and 2) *Wireless local area network* (WLAN) technologies (e.g. WiFi) which offer a high-bandwidth and low-latency service over a narrow geographic area. The handheld mobile devices are also equipped with multiple wireless network interfaces, which enable them to connect to the Internet. The most common trend in the mobile devices is to provision one network interface (NI) each for the WWAN (e.g. GPRS), WLAN (e.g. 802.11b) and fixed networks (e.g. USB connection). In some cases, these devices may have multiple simultaneous connections to the Internet, this capability is called multi-homing [Kaul05]. The MBU is in the multi-homed state when it has IP address assigned to multiple network interfaces at the same time.

The term *vertical handover* refers to a switchover from one network connection to the other network connection for the exchange of data. Multi-homing and vertical handover are utilized in several approaches (e.g. [Huan04], [Kaul05], [Mits03], [Mont04], [Waki02] and [Ylit03]) to provide mobile devices with high availability Internet connectivity, redundancy, fault tolerance, load balancing, cost-based communication decisions, low latency handover and QoS improvement. Considering these developments, we reason that depending on the network availability and MBU capabilities, during the patient movements, a vertical handover technique can be used to provide improved QoS for the delivery of biosignals. There exists no known prior work on the application of vertical handover technique in the area of mobile patient monitoring.

1.2 Research Problem

A mobile patient monitoring system considered in this thesis is the *MobiHealth Patient Monitoring System* (MHPMS) [Halt04]. The vision of the MHPMS system is that of providing ubiquitous medical care. This vision forsees that due to ever-advancing miniaturization of sensor devices and computers as well as ubiquitous deployment of wireless Internet networks, patients will be able to send full, detailed and accurate biosignals and receive medical care irrespective of their location. The origins of MHPMS system are to be found in [Jone01] leading to the MobiHealth project [Halt04, Jone06a, Jone06b]. This system is further developed in various European and Dutch projects [Jone07, Jone08]. Later projects which used the MobiHealth

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[3] In the recent developments, the 4G WWAN technologies such as LTE promise high data rates of 100 Mbps downlink and 50 Mbps uplink.

prototype system for the research and trials include *HealthService24*, *AWARENESS* and *Myotel*. The MHPMS has a focus on developing a generic BAN which can be specialized for any particular type of treatment by using a specific set of sensors and appropriate application functionality. E.g. a BAN may have different sensor sets for patients suffering from high-risk pregnancy, trauma, and cardio-vascular diseases. For details of these variants, we refer to [Buij03]. In Section 1.1.2, we state that in order to correctly execute the decision making step in the biosignal processing, the QoS requirements of biosignals delivery need to be fulfilled by the *extra-BAN communication path*.

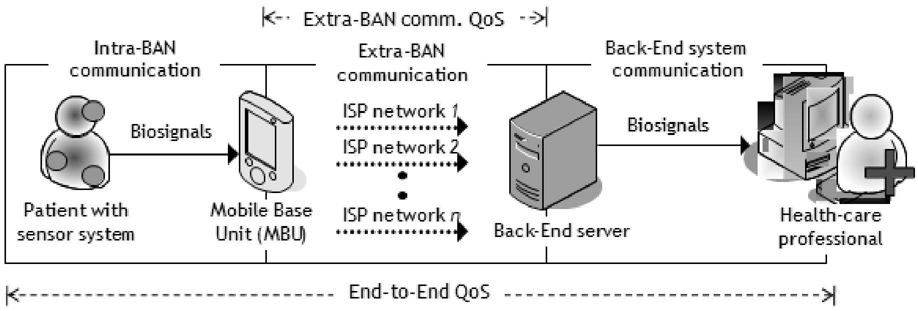

Figure 1.3: Abstract QoS View of the MobiHealth Patient Monitoring System

The extra-BAN communication in the MHPMS uses HTTP protocol for the transfer of biosignals. Since according to the *Internet Protocol suite*, HTTP is an application level protocol, the QoS requirements of biosignals delivery are also termed as application level QoS requirements. The abstract QoS view of the MHPMS is shown in Figure 1.3. The *end-to-end QoS* refers to QoS realized along the entire biosignals delivery path from the sensor system to the biosignals display terminal at the location of a healthcare professional. In comparison, the *extra-BAN communication QoS* refers to QoS experienced along the extra-BAN communication path from the MBU to the back-end server.

The extra-BAN communication network path consists of multiple heterogeneous networks. The first hop of this path is usually a wireless network to which the MBU is connected. In the day-to-day situation, the WLANs are deployed at multiple locations; however their geographic coverage is restricted. The mobility of a patient (e.g. transporting a trauma patient from the trauma location to the hospital) combined with uneven geographic distribution of the wireless networks result in the wireless networks availability changes surrounding the MBU. If the wireless network selected at a particular location does not provide enough geographic coverage, a patient mobility will result in the disconnection from this network. In these cases, the continuity of the mobile patient monitoring session is affected.

It is often a case that the QoS provided by the wireless networks is often lower than the QoS provided by the fixed networks[4]. Hence it is reasonable to assume that the *extra-BAN communication QoS* is bounded by QoS offered by a wireless network to which the MBU is connected. In 2004, the researchers in the MobiHealth project conducted nine trials of the MHPMS in four European countries with one of the goals to identify limitations and shortcomings of the existing and forthcoming WWANs. The results of these trials [Halt04, Wac04b] revealed the following problems regarding the use of WWANs for biosignals delivery:

Reversal of the Producer-Consumer Paradigm

Firstly, the WWANs are primarily designed for the applications in which a mobile device is a data consumer, i.e. normally, it sends smaller amount of data (e.g. HTTP request) and receive larger amounts of data (e.g. HTTP reply). Hence, the WWANs provision lower bandwidth for the uplink data while higher bandwidth for the downlink data. E.g. a GPRS network using *CS4* coding scheme provides 21.4 kbps uplink bandwidth using 1 timeslot while it provides 85.4 kbps downlink bandwidth using 4 timeslots [Ylia01]. However, in the MHPMS, the MBU is a *producer of data*. The existing WWANs are not designed to support transmission of high bandwidth data originating from the MBU. During the MHPMS trials, this was confirmed with the remark that the WWANs did not necessarily provide bandwidth required for the data streams constituting a higher number of biosignals. Secondly, the bandwidth available to the MBU is affected by the number of devices simultaneously transmitting data. The WWAN performance tests conducted during the MHPMS trial indicated degradation in the QoS performance while ten MBUs located in the same room simultaneously transmitted data over the WWAN. This shows that the MBUs may not actually realize the uplink bandwidth as per the WWAN specification. Moreover, it is a standard case that the QoS provided by a particular wireless network varies depending on the location and time [Wac09b]. This fact may result in a situation where a patient moves from the area of higher bandwidth to the lower bandwidth or experiences QoS performance degradation over a period of time. There is no provision in MHPMS to cope with this kind of changes [Halt04].

Power Consumption of the MBU

During the MHPMS trials, it was also observed that a MBU continuously transmitting biosignals data over the WWAN completely drains its battery in less than two hours [Wac04a]. Another study of the MHPMS [Wac09a] consists of transfer of 5.2 kbps data using a GPRS network, during which it is observed that this transfer drains the battery of the MBU (QTEK 9090 PDA) in less than two hours. This observation are also supported in [Halt04] that powering *always on* devices and

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[4] However, this situation is likely to change as wireless networks are evolving in capacity and heavy network centric applications such as video-on-demand utilize most of the available fixed network bandwidth in the Internet.

continuous transmission of biosignals continues to raise technical challenges such as faster drain of the battery life. From these observations, we deduce that for the cases in which it is not possible to recharge the MBU frequently, one of the hurdles in the duration of the continuous transmission of the biosignals is the power consumption of the MBU.

As motivated from the discussion above, we formulate our research problem as follows:

In the MHPMS, for the mobile patient monitoring cases requiring continuous biosignals delivery to the back-end system, how to use a vertical handover technique to satisfy QoS requirements of biosignals delivery in the environment characterized by patient mobility, deployment of multiple wireless networks technologies, uneven geographic distribution of the wireless networks, variable QoS characteristics of the wireless networks and limited battery capacity of the MBU?

1.3 Research Objectives

In this section, we outline stepwise research objectives in order to address the thesis research problem.

- ***Research Objective 1:*** *How to infer QoS requirements for the mobile patient monitoring cases requiring continuous biosignals delivery from the MBU to the back-end system?*

In the mobile patient monitoring cases requiring continuous biosignals delivery, patient's biosignals being received at the back-end system are used in a decision making process. From the viewpoint of healthcare professionals, in order to make an accurate decision about the patient's condition, it is necessary that certain clinical requirements during biosignals transmission need to be fulfilled. These requirements are the following: 1) Certain types of biosignals are must for the decision making; 2) The quality of biosignals being received should be good enough so that the decision making is not affected; 3) In case the healthcare professional expects the patient to take a certain action, then these instructions/feedback should be received by the patient to allow a certain reaction time. Since biosignals are transmitted using a wireless network communication path, we formulate this research objective to transform healthcare professional's requirements onto QoS requirements for the biosignals transmission. For the concepts of QoS, we refer to principles of QoS in the mobile computing environment presented in [Chal99]. In Chapter 4, we address this research objective with the help of three illustrative mobile patient monitoring cases.

- ***Research Objective 2:*** *How to use a vertical handover technique to maintain HTTP connectivity to the MBU in the events of patient mobility and network outage?*

Within the MHPMS, HTTP connectivity to the MBU is used to transmit patient's biosignals to the BESys. A common problem observed during the trials of mobile patient monitoring systems is wireless network unavailability due to patient's mobility.

Other reason for network unavailability is sudden outage of the existing network i.e. the network to which MBU is connected becomes unavailable due to unforeseen reasons such as power failure. For these reasons the second research objective is to investigate mechanisms to maintain HTTP connectivity to the MBU in the events of patient mobility or network outage. In both of these cases, a vertical handover technique is a proven way to maintain the connectivity. In the research literature, vertical handover refers to a switchover from one access network to the other access network for the exchange of data [Kass08].

A comprehensive state of the art of vertical handover management strategies is presented in Chapter 3. Two vertical handover mechanisms for addressing this research objective are presented in Chapter 5 and Chapter 6 respectively. These mechanisms are named as *Mobile Controlled Handover* (MCHO) mechanism and *Network Assisted Handover* (NAHO) mechanism, respectively. A vertical handover process is divided into three phases: *handover information gathering*, *handover decision making* and *handover execution* [Kass08]. The handover information gathering phase collects information required to identify the need for the handover and its execution. The handover decision making *(network selection)* phase determines the network suitable for the handover execution. The handover execution phase refers to the start using the selected network for the data transfer. Both, the MCHO mechanism and NAHO mechanism proposed in this thesis are based on the vertical handover process outlined in [Kass08].

- ***Research Objective 3:*** *If information about the QoS characteristics of wireless networks at a given location and time are known, how to take a network selection decision for the continuous delivery of biosignals?*

The QoS provided by a particular wireless network varies depending on the location and time [Wac09b]. Other factors which influence the QoS offered by a wireless network include the number of users simultaneously using the network connectivity [Halt04], signal fading and interference [Heus03] and the limit on the maximum number of mobile users [Lind02]. These factors may result in the situations where a patient moves from the area of higher bandwidth to the lower bandwidth or experiences a change in the QoS performance over a period of time. The wireless network providers tend to not disclose exact values of the QoS characteristics of a network. However, the peer research work on *QoS predictions* proposed in [Wac09b] is aimed at making available wireless network QoS information to the mobile devices in the location and time dimensions. The third research objective is to investigate how to take a wireless network selection decision in case the QoS predictions are available as one of the handover information.

A number of handover decision making algorithms are compared in [Stev06]. These include *multiplicative exponent weighting* (MEW), *simple additive weighting* (SAW), *technique for order preference by similarity to ideal solution* (TOPSIS) and *analytic hierarchy process combined with grey relational analysis* (AHP+GRA). The application data traffic classes considered in [Stev06] are the following: *conversational* (e.g. voice traffic), *streaming* (e.g. streaming video), *interactive* (e.g. web browsing) and *background* (e.g. email) [Dixi01]. A simulation based comparison of decision making algorithms in [Stev06] show that MEW, SAW and TOPSIS provide similar performance for all the above four traffic classes, while AHP+GRA provides a slightly higher bandwidth and lower delay for the interactive and background traffic classes. Among the six vertical handover approaches surveyed in Chapter 3, three approaches [Bala04, Ahme06, Wu09] use AHP algorithm in the decision making process. The AHP is a mathematical decision making technique [Saat90] that decomposes a network selection problem into several sub-problems and assigns a weight value for each sub-problem depending on the optimization objectives. The AHP algorithm is used in [Bala04, Ahme06] to select a wireless network that maximizes application's bandwidth requirements and minimizes delay and loss requirements. The solution to this objective using an AHP based handover decision making algorithm is presented in Chapter 6.

- ***Research Objective 4:*** *How to use the wireless network interfaces of the MBU to reduce its power consumption during the continuous delivery of biosignals?*

In Section 1.2 it is argued that power consumption of the MBU is one of the limitations on the duration of a mobile patient monitoring session. In the MHPMS, a MBU is solely used for patient monitoring purposes. Since the intra-BAN communication part of MBU is used to obtain biosignals and perform biosignals related processing, the only part which can be considered to reduce MBU's power consumption is the extra-BAN communication part. Referring to the architecture of mobile patient monitoring system presented in Section 1.1.2, a MBU uses wireless network interfaces for the extra-BAN communication. Our fourth research objective is to investigate how to use wireless network interfaces of a MBU to minimize its power consumption.

Normally, for the patient monitoring cases considered herewith, since a patient may be on the move, it is required to keep powered on all network interfaces of the MBU so that the wireless networks in the surroundings can be discovered. One of the handover information used in the NAHO mechanism is QoS predictions on the MBU. Since the QoS predictions provide information about availability of wireless networks in the location and time dimensions, it is not necessary to keep powered on unused network interfaces of the MBU and thus it may be possible to achieve power savings on the MBU. This research objective is addressed in Chapter 7 by proposing the variants of the NAHO mechanism that selectively turn off the unused NI on the MBU.

- ***Research Objective 5:*** *What are the gains achieved by proposed vertical handover mechanisms and what are the corresponding overheads?*

The proposed vertical handover mechanisms for the MHPMS are aimed at handling changes in the availability of wireless networks, provide sufficient extra-BAN communication QoS for the biosignals delivery and minimize power consumption on the MBU. To measure the gains achieved by these mechanisms and corresponding overheads, in this thesis we report a set of experiments, the results of which provide an indication of achieved gains and corresponding overheads. These gains/overheads are quantified in terms of the metrics derived from the review of related literature [Bern04, Chal99, Kass08] and peer experience in the MHPMS development [Alon02, Halt04, Wac09a]. These metrics quantify the following: *vertical handover performance, wireless network performance* and *power savings performance*.

Depending on the availability of context sources providing information necessary for handover decision making, the handover experiments reported in this thesis fall into two categories: *using an operational MHPMS system test bed* and *using simulations*. In particular, the performance evaluation of the MCHO mechanism is conducted using a real-operational MHPMS test bed that provides three types of Internet connectivity to the MBU, using a GPRS network, 802.11b network and fixed network connectivity via USB port. The performance evaluation of the MCHO mechanism is reported in Chapter 5. The NAHO mechanism makes use of QoS predictions to take a handover decision. Due to the unavailability of operational QoS predictions context source, the NAHO mechanism is evaluated using an extensive set of simulations, whereas the patient is assumed to travel distance of 8.470 km between the geographic coordinates of source location and destination location at the speed of 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 90 and 100 km/h respectively. In contrast, the MCHO mechanism experiments are conducted for stationary user in order to have better control of WLAN base-station for the experiments involving forced handover (manually switching on and switching off the used WLAN base-station). The performance evaluation of NAHO mechanism is reported in Chapter 6.

To analyze the possibility of power savings on the MBU, we proposed two variants of the NAHO mechanism which are $NAHO_{WLAN\text{-}OFF}$, and $NAHO_{WLAN\text{-}OFF,WWAN\text{-}OFF}$, respectively. For the experiments related to power savings analysis, we use network interfaces power consumption values of two mobile devices, namely QTEK 9090 PDA and IPAQ PDA. The power savings aspects of NAHO mechanism variants are reported in Chapter 7.

1.4 Scope and Outline of the Thesis

Since the healthcare is an ancient research discipline and relatively the mobile patient monitoring is a younger research discipline, herewith we briefly introduce scope of research conducted in this thesis.

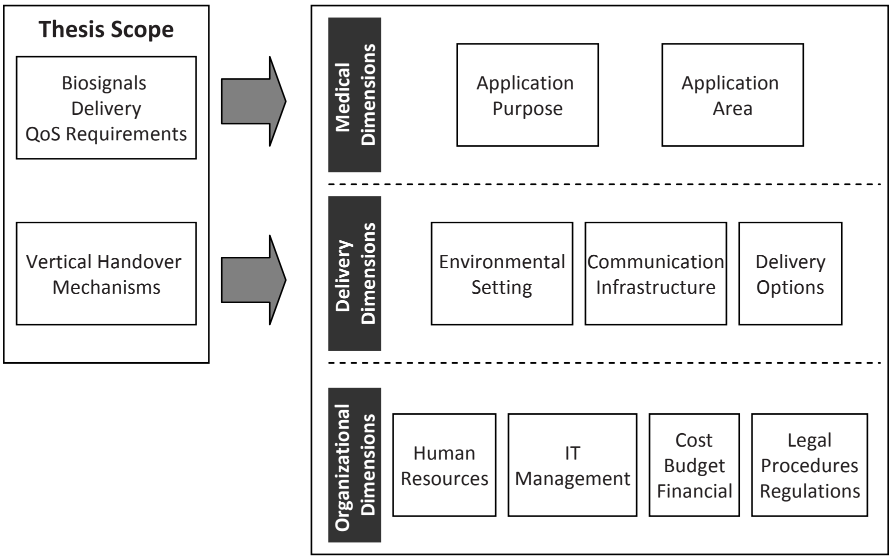

Figure 1.4: Mapping thesis scope onto the taxonomy of telemedicine efforts presented in [Tulu05]

A taxonomy of telemedicine efforts that helps to categorize and compare telemedicine efforts is presented in [Tulu05]. This taxonomy is shown in Figure 1.4. The organizational dimensions shown in this taxonomy are considered out of scope of this thesis. In the *medical dimensions*, we consider that the *application purpose* dimension of a mobile patient monitoring system is clinical i.e. it is used for diagnostic and treatment components of a patient care. The *application area* dimension refers to the medical domain such as cardiology and emergency room. The decision on acquiring particular biosignals of a patient is taken based on an application area. Accordingly, QoS requirements for biosignals delivery are determined. The delivery dimensions proposed in [Tulu05] are related to the way healthcare is delivered to an end-user. The delivery dimensions have a goal of supporting medical dimension's needs while delivering healthcare services. The *environmental setting* dimension of proposed handover mechanisms relates to delivering patient's biosignals from her current location to a computing device in the *back-end system*. The *communication infrastructure* dimension includes a set of heterogeneous wireless networks that provide Internet connectivity to the MBU. The *delivery options* dimension in [Tulu05] is classified into two communication groups: *synchronous* and *asynchronous*. The continuous patient monitoring is synonymous to the synchronous communication because the biosignals are being acquired from the patient's body and it is required to send them to a healthcare professional immediately. Along with the patient, the healthcare professional is also a user of patient monitoring service, whose primary task is to receive current and accurate patient information and perform decision making based on the patient's conditions and needs [Vash07]. The work reported in this thesis proposes vertical handover mechanisms in the delivery dimensions in order to satisfy needs of continuous biosignals delivery as determined by the medical dimensions.

This thesis is organized as follows: Chapter 2 provides a number of concepts, definitions, assumptions and architectural considerations necessary to understand further chapters. The state of the art of mobile patient monitoring systems, vertical handover mechanisms and QoS predictions is presented in Chapter 3. The QoS requirements of continuous biosignals delivery and handover information requirements for the proposed vertical handover approaches are elicited in Chapter 4. Chapter 5 elaborates on the architecture, experimentation and results of the *mobile controlled handover* (MCHO) mechanism. The architecture, experimentation and results of the *network assisted handover* (NAHO) mechanism are detailed in Chapter 6. The potential of NAHO mechanism for power savings on the MBU is analyzed in Chapter 7. The simulation results of the NAHO mechanism encourage us to implement NAHO mechanism in practice. However, the practical realization of NAHO mechanism needs to address a number of issues. These issues, conclusions and directions for the further research are discussed in Chapter 8. The thesis outline is shown in Table 1.1.

Table 1.1: Outline of the thesis

No.	Chapter Title	Aim	Description
2	Concepts, Definitions, Architectural Considerations and Assumptions	Provides various information and concepts necessary to understand this multi-disciplinary thesis.	• New definitions of M-Health and mobile patient monitoring. • Architectural building blocks of the proposed handover mechanisms • Assumptions on which the further research is based
3	State of the Art	Survey of the mobile patient monitoring systems, vertical handover approaches and QoS predictions	• Comparison of six mobile patient monitoring systems • Comparison of six vertical handover management approaches • Introductory information about QoS predictions
4	Requirements Elicitation	Addresses research objective 1	• Elicitation of the biosignals delivery QoS requirements in the mobile patient monitoring systems • Elicitation of the handover information requirements for the proposed handover approaches
5	Mobile Controlled	Addresses research objective 2 and research objective 5	Architecture, implementation details, experimental setup, description of

	Vertical Handover Mechanism		experiments and obtained results of the MCHO mechanism
6	Network Assisted Vertical Handover Mechanism	Addresses research objective 2, research objective 3 and research objective 5	Architecture, implementation details, simulation setup, description of the simulators, description of the experiments and obtained results of the NAHO mechanism
7	NAHO Mechanism for Power Savings	Addresses research objective 4 and research objective 5	Description of the NAHO variants for the power savings, description of the experiments and obtained results
8	Conclusions and Future Work	The end chapter of the thesis	• Research objective-wise thesis conclusions • General conclusions • Issues to be considered while implementing NAHO mechanism in practice • Directions for the future work

Chapter 2

Concepts, Definitions, Architectural Considerations and Assumptions[5]

Due to immediate noticeable benefits and potential of achieving good return on investments, the *ICT in healthcare* has attracted significant attention among the researchers and industry. However, this has given rise to a plethora of ICT in healthcare terms e.g. *E-Health*, *telemedicine*, *M-Health*, *wireless medicine*, *wireless telemedicine, tele-treatment* and *tele-monitoring*. Similarly, depending on the expertise and domain, the researchers have different notions about terms such as *context*, *QoS*, *handover* and *services*. This chapter introduces and provides definitions of these terms and concepts within the context of reported work. Apart from this, this chapter also provides detailed architecture of the *MobiHealth Patient Monitoring System* (MHPMS).

This chapter is organized as follows. Section 2.1 defines terms related to the ICT in healthcare domain, with an emphasis on the mobile patient monitoring. Section 2.2 introduces a few terms related to mobile computing and networking. A few of the mobile computing terms are presented in Appendix A. The service oriented computing related concepts with a focus on nomadic mobile services are illustrated in Section 2.3. Section 2.4 discusses implementation of middleware for the provisioning of nomadic mobile services. Section 2.5 introduces context-aware computing and explains a layered model that is popular in the development of context-aware computing systems. The MHPMS is described in Section 2.6.

2.1 Identifying Mobile Patient Monitoring within the ICT in Healthcare

The scope of ICT as defined by the *World Bank*[6] consists of hardware, software, networks, and media for the collection, storage, processing, transmission and

[5] A part of this chapter is based on our work published in [Halt06] and [Pawa07a].
[6] The world bank website: *http://www.worldbank.org*

presentation of information (voice, data, text, images), as well as related services. The *United Nations Global Alliance for ICT and Development*[7] states that the *E-Health* is the use of ICT in health. According to the systematic survey of E-Health definitions published in [Oh05], the most popular and comprehensive definition of E-Health is due to Eysenbach [Eyse01]:

E-health is a field in the intersection of medical informatics, public health and business, referring to health services and information delivered or enhanced through the Internet and related technologies. In a broader sense, the term characterizes not only a technical development, but also a state-of-mind, a way of thinking, an attitude, and a commitment for networked, global thinking, to improve health care locally, regionally, and worldwide by using information and communication technology.

In this thesis, we refer to the above definition of E-Health. However, considering the scope of this thesis, we restrict ourselves only to the technical developments contributing to E-Health. From the above definition, it is clear that in the E-Health domain, ICT is being used for enhancing and delivering health services and related information. These observations match with those concluded in the survey of E-Health definitions in [Oh05]; it is stated that the ICT is meant to expand, assist or enhance human activities, rather than to substitute these. Moreover, E-Health may not have any adverse, negative, harmful or disadvantageous effects.

As described in the *history of E-Health* [Tan05], in the early 1950s, the major hospitals attempted to use mainframes for the batch processing of health-related information. However, these attempts were unsuccessful due to the lack of support from the hospital management, lack of funding and the lack of knowledge required to use the automated systems. From the early 1960s through the 1970s, there were further numerous attempts of prototyping the hospital information systems. The first successful prototype was the *Technicon system*, following which large-scale data processing applications in medicine and health record systems began around mid-1970's. In the early 1980's, because of the rise of miniature computers, their affordable costs and networking, the health data processing moved from the mainframes to the distributed *health management information systems*. Further, the health networking and telecommunications technologies opened a new interest for the *E-clinical decision support* and *E-medicine* applications. In the mid 1990's, this interest spread into other areas of healthcare which are *E-commerce applications*, *E-nursing support systems* and *E-homecare systems* [Tan05]. In the later stages, the emergence of E-mail, wireless Internet and the World Wide Web resulted into the E-Health applications in the existence today. A few of these applications are *automated patient alerts*, *E-referencing*, *E-prescriptions* and *E-health communities*. A number of examples of the E-Health systems are illustrated in [Tan05]. The deployment of nationwide or regional *electronic patient records* (EPR) is another advance in the E-Health. EPR offers new methods of storing, manipulating and communicating medical information of all possible types including text, images and videos [Roge00].

[7] The United Nations Global Alliance for ICT and Development website: *http://www.un-gaid.org*

A commonly used term in the healthcare sector is *telemedicine*. A few of the researchers consider the terms telemedicine and E-Health synonymous with each other. The term telemedicine is constructed from two components: *tele*, meaning distance, and *medicine* which mean[8] '*The science and art of the maintenance of health and the prevention, alleviation or cure of disease*'. A definition of *telemedicine* encompassing these aspects is provided by the *Department of Essential Health Technologies of World Health Organization* [Deht03] as follows:

The delivery of health care services, where distance is a critical factor, by health care professionals using ICT for the exchange of valid information for diagnosis, treatment and prevention of disease and injuries, research and evaluation, and for the continuing education of health care providers, all in the interest of advancing the health of individuals and their communities.

From this definition, it is clear that the telemedicine is a part of e-health, while the latter is not necessarily concerned with the distance. Both, the *European Space Agency Telemedicine Alliance*[9] and *American Telemedicine Association*[10] comment that *telehealth* has a broader meaning than telemedicine, however it is restricted in scope compared to the E-Health. In addition to telemedicine, telehealth also encompass educational, research, and administrative uses as well as clinical applications that involve nurses, psychologists, administrators, and other non-physicians [Fiel02].

Depending on the way the medical data is delivered, the telemedicine is further classified into two groups: *synchronous* and *asynchronous* [Alle95, Lau02, Tulu05]. In the synchronous telemedicine, the medical information is shared between two or more number of participants simultaneously – at the same time. E.g. *patient video conferencing, real-time biosignals delivery*. In comparison, in the asynchronous telemedicine, the medical data transactions occur at different points in time. E.g. *store and forward, email, web pages*. Both of the synchronous and asynchronous telemedicine applications are beneficial for the patients [Alle95].

In his research article titled 'E-Health Prospects' [Tan05], Joseph Tan describes that the emergence of *Mobile Health* (M-Health) is natural because of the transition and transformation of the traditional ICT applications to the wireless platforms. Along with conducting traditional E-Health tasks such as viewing patient's records on a mobile device or transmitting prescriptions to pharmacies, the new ability added to the E-Health domain by mobile technologies is that of exploiting an immediate presence of mobile devices with the patient to acquire and deliver health related information.

Figure 2.1 shows chronological transition from e-health applications to M-Health applications. *Mobile patient monitoring* is one of the M-Health applications [Tan05].

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[8] According to the Longman dictionary of the English language (1984).

[9] *http://www.esa.int/telemedicine-alliance*

[10] *http://www.americantelemed.org*

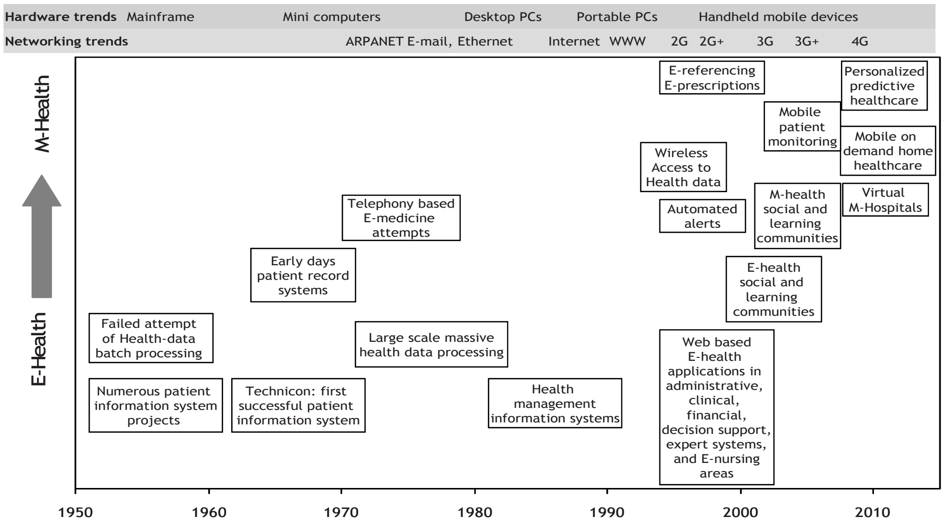

Figure 2.1: Transition from the E-Health to the M-Health

Similar to E-Health, there exist a number of definitions for M-Health. One of the most popularly cited definition is by Istepanian et. al. [Iste05]:

M-Health is the emerging mobile communications and network technologies for healthcare systems.

However, we think that this definition is focused more on the mobile computing aspects than the mobility aspects of persons involved in the healthcare system. Hence herewith we redefine M-Health as:

M-Health is an appliance of the mobile computing, wireless communications and network technologies to deliver or enhance diverse healthcare services and functions in which the patient has a freedom to be mobile, maybe within a limited area.

Our definition of M-Health stresses on the mobility aspects of the stakeholders in the healthcare system. In particular, we focus on the mobility of a patient. Commonly, the patient is a person who is receiving a medical care. The patient monitoring[11] is the continuous or frequent periodic measurement of the physiological processes such as blood pressure, heart rate, respiration of a patient. The physiological processes that provide indications about the functioning of certain specific body functions and those that can be measured and monitored from biological beings are commonly referred to as *biosignals*. Some of the common biosignals are *ElectroEncephaloGram* (EEG), *MagnetoEncephaloGram* (MEG), *Galvanic Skin Response* (GSR), *ElectroCardioGram* (ECG) and *Heart Rate Variability* (HRV).

[11] According to the online medical dictionary *http://www.medicaldictionaryonline.info/*.

There exist a variety of terms for the use of ICT in patient monitoring, e.g. *telemonitoring*, *remote patient monitoring*, *wireless patient monitoring* and *mobile patient monitoring*. The *telemonitoring*[12] is a process of using audio, video and other telecommunications and electronic information processing technologies to monitor the health status of a patient from a distance. Telemonitoring and remote patient monitoring are synonymous to each other [Meys05]. In the current state of telemonitoring, [Meys05] it is noted that apart from monitoring sick patients, the telemonitoring also refers to monitoring healthy individuals including athletes and astronauts.

We consider that the mobile patient monitoring is a part of remote patient monitoring. In the remote patient monitoring, the entire healthcare tasks can be conducted solely using wired communication links that restrict movements of a patient. E.g. a digital ECG transmission system described in [Spar04] has a provision to transmit the ECG of a patient to the remote cardiologist using a fixed phone line modem. We specifically consider that during the mobile patient monitoring, the patient has a freedom to be mobile. Given this, we define the mobile patient monitoring as following:

Mobile patient monitoring is the continuous or frequent measurement and analysis of the biosignals of a mobile patient from a distance by employing mobile computing and wireless communication technologies.

The relationship between a number of paradigms described herewith and the position of mobile patient monitoring within them is summarized in Figure 2.2.

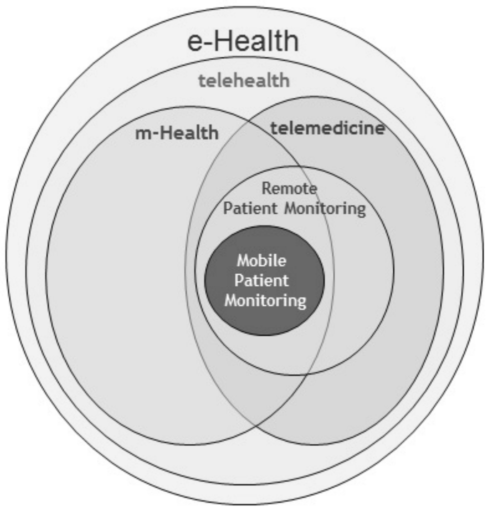

Figure 2.2: Relationship between the mobile patient monitoring and other E-Health paradigms

[12] According to the American Telemedicine Association (*www.americantelemed.org*).

2.2 Mobile Computing and Networking Related Terms

In this thesis, we use a number of terms related to mobile computing and computer networking. Herewith we present a selected few terms. The other related terms are provided in Appendix A.

- *Multihoming*: A number of mobile devices are equipped with multiple network interfaces, which enable them to connect to the Internet via different wireless networks. In certain cases, these devices have multiple simultaneous connections to the Internet, this capability is called *multi-homing* [Kaul05]. Multi-homing is typically used to describe a computing device rather than an ISP network. There exist a number of variants of multihoming such as *single link - multiple IP address* or *multiple interfaces - single IP address* and *multiple links, single IP address*. In this thesis, we consider multihoming in terms of *multiple interfaces – one IP address each*. The *Mobile Base Unit* (MBU) is in the *multihomed state* when it has IP address assigned to both of the WLAN and WWAN network interfaces at the same time.
- *Vertical handover:* Typically, the vertical handover refers to a switchover from one network connection to the other network connection for exchanging of data. In our specific case, it refers to the change of the IP network connection on the MBU for delivering biosignals. The other type of handover known as a horizontal handover refers to switchover between access points such as cellular towers while continuing to use the same wireless network for the data transfer. Since in this thesis, we are not dealing with the *horizontal handover*, we use the word *handover* to signify the vertical handover.
- *User initiated handover*: When the handover process is initiated manually by a person or triggered by user preferences and policies, then it is referred to as user initiated handover [Bern04].
- *Forced handover*: In contrast to the user initiated handover, forced handover is triggered by physical events regarding availability or unavailability of a wireless network [Bern04].
- *Seamless handover*: This is the type of handover where the transition to a new network is transparent to the application on a mobile device exchanging data [Kass08].
- *Mobile Controlled HandOver (MCHO)*: In a mobile controlled handover, all required information for taking a handover decision is available on a mobile device and the mobile device makes the handover decision on its own.
- *Network-Assisted HandOver (NAHO)*: In this type of handover, along with the information available locally, the information collected from the information sources in the fixed network is also used by a mobile device for taking a handover decision. The mobile device makes the handover decision on its own.
- *Quality of Service (QoS)*: The QoS is a performance of a data delivery service offered by a network communication path. This performance is measured in terms of QoS characteristics. The QoS characteristics we focus on are *goodput*, *round trip time* and *data loss ratio*. These characteristics are described as follows:

- *Goodput*: The goodput refers to the useful amount of information delivered per second to the application. The goodput is comparable to the *application level data rate* described in [Chal99]. For the continuous biosignals delivery cases, the goodput refers to the amount of biosignals received per second by the BESys. We name it as the *extra-BAN communication goodput*.
- *Data loss ratio:* The data loss ratio refers to the proportion of total data that does not arrive as sent [Chal99]. For the continuous biosignals delivery cases, the data loss ratio refers to the amount of biosignals data per second which cannot be sent to the back-end system. The data loss can occur if the goodput requirement for the biosignals transmission is higher than the actual extra-BAN communication goodput.
- *Round Trip Time (RTT)*: The round trip time is generally defined as the time elapsed between sending a request to the destination and receiving the corresponding reply. The RTT is comparable to the *response time* in [Chal99]. For the continuous biosignals delivery cases, we regard RTT as the time elapsed between the transmission of a message originating from the MBU and receiving corresponding reply from the back-end system.

2.3 Service Oriented Computing Related Concepts

In recent years, the *Service Oriented Computing* (SOC) has evolved as a primary paradigm for the development of the distributed systems. In this thesis, we adopt the SOC terminology as it appears in [Papa06] and [Huhn05]. The SOC is defined as a computing paradigm which utilizes services as fundamental elements for the development of distributed applications or solutions. A *service* is defined as an autonomous, platform-independent computational entity that can be described, published, discovered and used in a platform independent way. Because of these characteristics, any piece of code and any software component can possibly be reused and transformed into a service which is made available in the network.

The SOC relies on the *Service Oriented Architecture* (SOA) that provides a way to model a piece of code or a software component as a service and moreover provides a support infrastructure for interconnecting a set of services, whereas each service is accessible through standard interfaces and messaging protocols [Papa06]. In the M-Health, the principles of SOC are applied to design frameworks for delivery, sharing and computing of the M-Health information. E.g. *fault tolerant web information system* [Balb08]. The architecture of the MobiHealth patient monitoring system and the context-aware vertical handover mechanisms researched in this work are based on the principles of *Service Oriented Computing* (SOC).

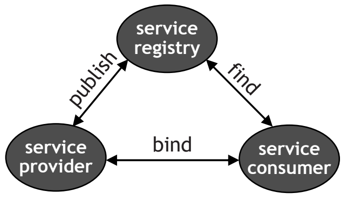

Figure 2.3: Components of the service oriented architecture

A basic SOA relates the following three types of roles: *service provider*, *service registry*, and *service consumer* (*client*). As shown in Figure 2.3, interactions between these roles involve *publish*, *find* and *bind* operations. A service provider is responsible for publishing a description of its services in a service registry. A service consumer looks for a suitable service in the service registry and binds to this service in order to utilize the service.

2.3.1 Jini Technology

To date, there exist a variety of technologies which implement the SOA paradigm; E.g. *Web Services*, *OSGi*, *Jini* and *UPnP*. Since the components of MHPMS back-end system are based on Jini technology, we present herewith a brief description of Jini. The Jini system architecture consists of three categories: *infrastructure*, *programming model*, and *services* [Wald99]. The Jini infrastructure is built on top of the *Java Remote Method Invocation* (RMI) system and provides a set of components that enables building a federated Jini system, where the services are entities within the federation. The Jini federation refers to an informal group of services and their clients that use Jini-defined interaction patterns. The basic infrastructure consists of a *discovery protocol* and a *lookup service*. The discovery protocol allows an entity willing to join a Jini federation to find a lookup service. The lookup service acts as a service registry where a service provider publishes services and a service consumer can find the service. The service provider discovers the Jini lookup service and registers a *service proxy* with it. The service proxy implements all service interfaces and contains logic to communicate with the service. It is also downloadable from the network. A Jini client (consumer) discovers the lookup service and requests a desired service either using a service interface or description or both. If this type of service is registered with a lookup service, the corresponding service proxy is returned to the client. To utilize the service, the client instantiates a service proxy and invokes implemented interface methods. The programming model includes models for *leasing*, *event notification*, and *transactions*.

The Jini system is Java centric because it is built on top of the Java environment and it heavily relies on features widely available within the Java platform. The Java environment provides homogeneity by turning a heterogeneous network of computing entities into a homogeneous collection of the *Java Virtual Machines* (JVMs). The *write-once-run-everywhere* property of Java byte codes allows an object code to be moved and dynamically loaded into a running process. These properties of Java are greatly used by the Jini system. Moreover, a Jini system design relies on the Java security model to allow fine-grained control of operations that can be performed by any code.

2.3.2 Nomadic Mobile Service

Today, handhelds are characterized by a higher amount of processing power, increased memory capacity and availability of multiple wireless network interfaces for connecting to the WWAN and/or WLAN. The mobility, portability and connectivity features of handhelds have enabled convenient personal applications, turning them into a personal information delivery platform. Until recently, the SOA research has been focused on the use of handhelds in the role of a service user, e.g. [Tian04]. However, a handheld in the role of a service provider enables new scenarios such as a *context information provider* (e.g. location, agenda), *content provider* (e.g. live video from an integrated camera or patient biosignals from the BAN), *controller* (e.g. controlling consumer electronic equipment) and *gateway* for offering certain functionality to the world (e.g. providing paramedics assistance). These developments have resulted in the rise of *Nomadic Mobile Service* (NMS) [Pawa07a]:

A nomadic mobile service is a service oriented computing based service offered by the Internet capable mobile host such as a handheld device, mobile phone or an embedded device which publishes this service in the service registry so that the client located anywhere in the Internet is able to find and bind to it.

The term Internet capable means that the mobile host has an access to the Internet using a wireless network. A mobile host roams from one mobile network to another which gives nomadic characteristics to the services it hosts. A comparative study of three NMS provisioning architectures is done in [Pawa07a]. One of these approaches is referred to as *Mobile Service Platform* (MSP) which uses the concept of *Jini Surrogate Architecture* [Sun01] for the *publish*, *find* and *bind* operations.

2.3.3 Jini Surrogate Architecture

This section provides in brief concepts related to the Jini surrogate architecture [Sun01]. A nomadic mobile service based on the concept of Jini surrogate architecture is illustrated in Figure 2.4. The MobiHealth Patient Monitoring System (MHPMS) utilizes MSP and the concepts of Jini surrogate architecture to publish the biosignals delivery as a nomadic mobile service in the Internet.

As described in Section 2.3.1, a computing device willing to offer a service in the Jini federation should host a JVM. However, for the devices which do not have sufficient resources to host a JVM, the Jini surrogate architecture provides a solution. The device hosts a service which we refer as a *device service*. The other device known as a *surrogate host* has memory and computing power to support a full JVM. A *surrogate* is an object that resides in the surrogate host and acts as a representation of the device service for the Jini network. Together, the device service and its surrogate form a nomadic mobile service.

An *interconnect* is a logical and physical connection between a device and its surrogate host. The interconnect protocol specifies interactions between a device and its surrogate host and it can be implemented using several communication protocols, such as IP, USB and IEEE1394 (serial bus interface standard). E.g., MSP implements the interconnect protocol using HTTP. As described in [Sun01], any Interconnect implementation should fulfill at least three features: *device discovery*, *surrogate upload* and *keep-alive*. In Interconnect, a device and its surrogate host find each other using an operation called as *discover*. Once discovery is performed, the surrogate of a device service must be acquired. E.g., a device service may specify an URL to the surrogate host from where to download its corresponding surrogate. Later a surrogate host instantiates the surrogate, which may use Java byte code and computational resources provided by the surrogate host. The surrogate performs other necessary tasks on behalf of the device, for instance, joining the Jini federation. An *interconnect* also specifies mechanisms to ensure that a device service and its surrogate are reachable to each other, e.g. using *keep-alive messages*. If the device is no longer reachable for a certain reason (e.g. due to a network failure), then the surrogate host deactivates a surrogate and a service is removed from the Jini federation.

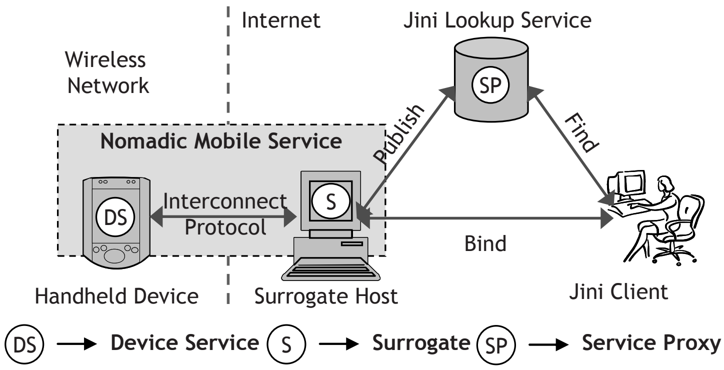

Figure 2.4: Nomadic mobile service according to the Jini surrogate architecture concept

2.4 Implementation of the Mobile Service Platform

The architecture of MSP is based on the principles of Jini surrogate architecture. There are two main parts of the MSP implementation [Halt06]. The first part consists of *device service*, *surrogate* and interactions between them. The second part consists of *surrogate*, *Jini lookup service*, *client* and interactions between them. A device service is usually implemented using the J2ME technology. MSP provides a set of custom APIs necessary for managing lifecycle of a device service, interactions within the device service and surrogate and administering these interactions. The second part of MSP implementation is based on Jini service provisioning. The MSP consists of HTTP implementation of the Interconnect protocol to fulfill mechanisms of *device discovery*, *surrogate upload* and *keep-alive* as well as message exchange between a device service and its surrogate [Halt06]. This implementation is known as the *HTTPInterconnect*. The *HTTPInterconnect* consists of three modules: *Messages*, *IO* and *Interconnect*. The elements of MSP are shown in Figure 2.5.

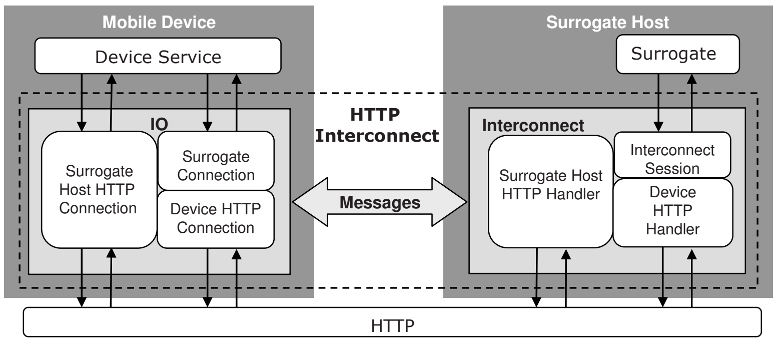

Figure 2.5: HTTPInterconnect implementation – showing three modules – IO, Messages and Interconnect

2.4.1 Messages

The *Messages* package defines a structure of messages exchanged between a device service and its surrogate. This package contains functionality for encoding and decoding data that is sent in these messages. The message begins with a *serviceId*, followed by an *operationId* and a *sequenceId*. The *serviceId* is an ID of a device service that sent the message (or an ID of a device service the message is destined for, when sent from the surrogate). A message may trigger an operation which has an associated operation type. Each operation type offered by the device service to its surrogate and vice versa triggers a certain operation. The *operationId* is a unique ID that is given to the operation type. The *sequenceId* identifies a message order. The body of a message contains data specific to the operation to be performed by a message. The messages module supports the following three types of interactions:

- *One-Way messaging*: One-way messaging allows for unconfirmed message delivery between a device service and its surrogate. This type of message does not have a corresponding reply.
- *Request-Response messaging*: The request-response messaging supports a reliable message delivery. A request message must have a corresponding reply message. An example of this message is *Keep-Alive message*, which is sent by a device service at fixed intervals to its surrogate which acknowledges this message by sending a response.

- *Streaming*: Streaming supports exchange of continuous data (streams) between a device service and its surrogate. In MHPMS, this allows a (near) real-time delivery of biosignals to the back-end system.

The IO module has a component known as *MessageWorker* for the transmission of one-way and request-reply messages and another component named as *StreamWorker* for the transmission of streaming messages, respectively.

2.4.2 Input/Output (IO) and Interconnect

The *IO* module contains a part of *HTTPInterconnect* that resides on the mobile device. This package handles all the messages sent to and from a device service. The key objects of IO module are the *SurrogateHostHTTPConnection*, *SurrogateConnection* and *DeviceHTTPConnection*. The *Interconnect* module contains a part of *HTTPInterconnect* in the surrogate host. This package handles activation and deactivation of surrogates and all the messages sent to and from the surrogates. The essential objects of *Interconnect* module are *SurrogateHostHTTPHandler*, *InterconnectSession* and *DeviceHTTPHandler*.

On start-up, a surrogate host initiates *SurrogateHostHTTPHandler* object to handle received requests. When a device service initiates, it sends a registration request to the *SurrogateHostHTTPConnection*. This object represents a connection to the surrogate host. If there are no device services registered before, on receiving a registration request, the surrogate host creates *DeviceHTTPHandler* object to handle requests from the mobile device hosting the service. The surrogate host later returns a *DeviceHTTPConnection* object to the mobile device. Once the *DeviceHTTPConnection* is available, the device service sends a *surrogate activation request* to the *DeviceHTTPHandler*. A surrogate and *DeviceHTTPHandler* share an *InterconnectSession* object which is created by the surrogate host as a part of surrogate activation. A surrogate host sends messages to the device service via the *InterconnectSession*. If the activation request succeeds, *DeviceHTTPConnection* returns a *SurrogateConnection* to the device service. This *SurrogateConnection* represents a connection to the surrogate and it allows a device service to send messages to its surrogate. In case of the request-reply message, *DeviceHTTPConnection* receives a reply and determines corresponding device service for the message. In principle, a *DeviceHTTPConnection* can support up to 255 surrogate connections, thus allowing 255 device services to run on a mobile device.

When a device service stops, a surrogate host needs to be notified of it so that it deactivates corresponding surrogate. For this purpose, a device service requests *deregister surrogate operation* via *SurrogateHostHTTPConnection*. This request is forwarded to *DeviceHTTPConnection*, on receipt of which *DeviceHTTPConnection* creates a *deregister message* and sends it to the surrogate host. The surrogate is deactivated and a confirmation is notified back. As part of the surrogate deactivation, *InterconnectSession* existing between *DeviceContextHandler* and the surrogate is terminated. The *DeviceHTTPConnection* removes the corresponding *SurrogateConnection*. If the terminated surrogate is the only surrogate for this device, *DeviceHTTPConnection* is also closed.

MSP uses *Madison* as an implementation of the surrogate host designed and implemented by Sun [Sun03]. Madison offers an interface for device discovery, activation and keep-alive management which is implemented by *HTTPInterconnect* protocol.

2.4.3 Key Features of the HTTPInterconnect

To address the problem of low bandwidth and high latency in the WWAN networks, *HTTPInterconnect* features a number of optimizations. Along with the provision for One-Way messaging, a number of messages for the same device may be combined in one HTTP request. Additional improvement is achieved with HTTP chunking [Kozi05], where the messages are conveyed as chunks of one long-term HTTP request.

One of the problems with the device service is that this service is not fixed and changes its location resulting in variable IP address assignments. The 2.5/3G wireless network operators typically assign an IP address to a mobile device dynamically from the private address space at the establishment of a wireless connection [Rekh96]. *Network Address Translation* (NAT) inhibits connection from the public Internet to a device behind a NAT router. When a device enters a network without a DHCP server, it may assign itself an IP address using the *Automatic Private IP Addressing* (APIPA) [Kozi05]. However this address is not known globally. Assigning a permanent IP address to a mobile device and ensuring its reachability using mechanisms such as Mobile IP is a promising solution. However, it is subject to availability of IP addresses and price that the network operator charges. To solve this problem, MSP uses a *piggybacking* technique. A device periodically sends *HTTP request* message to a surrogate host. The message from the surrogate to a device service is piggybacked in *HTTP Response* to *HTTP Request* received from the device. Since the routers keep connection alive for routing the response, this technique solves the communication problem with the devices which are also behind NAT. For further information on the MSP, we refer to [Halt06].

2.5 Context Aware Computing Related Concepts

Compared to early days of computing, present day sensor and mobile devices are smaller in size and are capable of collecting, processing and transmitting a variety of data, which can be efficiently analyzed to derive higher level of interesting information. Combined with the need to provide personalized services, this has resulted in a number of user-centric computing paradigms, such as *ubiquitous computing*, *pervasive computing*, *ambient intelligence*, *location-based computing*, *calm computing*, *intelligent* or *smart computing*, and *emotional computing*. The *context-aware computing* [Schi94] is closely related to these paradigms, and it provides a framework illustrating guidelines for the development of systematic information processing channel. This channel receives input from the software and hardware sensors and it's output is used to achieve adaptive behavior aimed by the above paradigms.

Due to an abundant presence of entities providing context information in the patient environment and simple and clear application guidelines, the researchers in M-Health domain increasingly use context-awareness for achieving personalization in the M-Health systems. The examples of context-aware M-Health systems include framework for medical video delivery which considers both, the network and patient context for proper coding of medical video data [Douk07], context-aware workflow management framework to help medical experts constructing and adjusting on-the-fly context-aware M-Health application workflows [Sald06] and context-aware business application service co-ordination in mobile computing environments [Ng06]. In the remaining part of this section, we identify a number of concepts and terms related to context-aware computing.

2.5.1 Context

One of the most debatable issues is the definition and scope of the term *context*. A number of definitions of context are surveyed in [Chen00] and [Bald07]. Herewith we follow Dey's generic definition of context [Dey01]:

Context is any information that can be used to characterize the situation of an entity, where the entity is a person, place, or object that is considered relevant to the interaction between a user and an application, including the user and application themselves.

The more specific classification of context is provided in [Chen00] as follows.

- *Computing* (and *communication*) *context* refers to the information such as network connectivity, communication costs, bandwidth, and other resources such as printers, displays, and workstations.
- *User context* includes information such as user's profile, location, and people nearby, even the current social situation.
- *Physical context* consists of information such as lighting, noise levels, traffic conditions, and temperature.
- *Time context* refers to the temporal information such as time of a day, week, month, and season of the year.

2.5.2 Layered Model of Context-Aware Computing

A structured development of context-aware computing system is generally based on a layered model. Based on the extensive literature survey, [Wac09c] outlines a layered model of context-aware computing system. This model consists of the following five layers as illustrated in Figure 2.6.

At the *physical layer* context sensors (or other context objects) produce context information in a raw format, e.g. RF signal strength of the WiFi access points. These context sensors can be *physical*, *virtual* or *logical*. The physical sensors capture environmental data, e.g. light, visual context, audio, motion/acceleration and location. The virtual sensors obtain context data from the software entities such as electronic calendar. The logical sensors may combine data obtained from physical, virtual or other logical sensors as well as other information sources (e.g. databases) to produce higher level context information.

At the *context data layer* raw context data is retrieved and pre-processed for storage or dissemination. This layer contains drivers for physical sensors and APIs for virtual and logical sensors. E.g. coordinates of a user's location can be computed based on RF signal strength of three WiFi access points. The entities constituting context data layer are herewith referred as *context sources*.

The *semantic layer* contains objects that process context data obtained from context sources and transform it into a form meaningful for inferring further context, and store it for later retrieval. E.g. the semantic layer entities may indicate that based on computed location, a user is at home. We refer to the semantic layer entities as *context processors*.

The *inference layer* uses correlated information obtained from the semantic layer together with (dynamically learned or static) inference rules (or policies) to determine certain decision(s) relevant to the applicable rule(s). We refer to an entity relevant to this layer as the *context reasoner*. E.g. in case the inference rule refers to the occurrence of patient emergency, the context reasoner may determine the caregiver nearest to the patient.

The *application layer* is notified by an inference layer of the inferred decision, based on which a context-aware application may take a certain action. Continuing the example above, the application instructs a caregiver to rush to the patient's location.

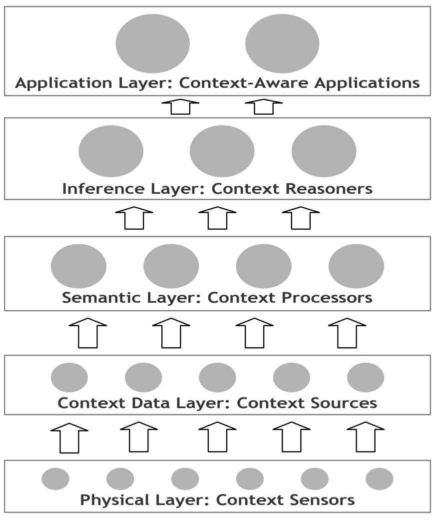

Figure 2.6: Layered model of a context-aware system

Inherent to the layered model of context-aware systems is a separation of concerns between context acquisition, processing, reasoning and its usage at the application layer. At any higher layer, this architecture permits combination of inputs, i.e. context information from one or more objects on any of the lower layers. This architecture supports an iterative context-aware systems design; emphasizes modularity and composability of context-handling components and appropriate allocation of responsibilities. Hence, it is adapted by many researchers (e.g. [Dey01, Gu05, Henr05]) to design their context-aware systems.

A nomadic mobile service hosted on a mobile device may also provide context information. In this case, it acts as a context source. In our implementation, a context source provides following methods [Pawa07d]:

1. *getContext()* allows a client to obtain context information.
2. *subscribeContext()* allows a client to subscribe for context updates. The client should provide a callback interface over which the context change notification is sent.
3. *unsubscribeContext()* allows a client to cancel subscription for the context updates.

2.6 MobiHealth Patient Monitoring System

The origin of *MobiHealth Patient Monitoring System* (MHPMS) can be traced back to the MobiHealth project[13]. The MHPMS enables mobile patient monitoring by interfacing sensors with the handhelds and using wireless network for the delivery of biosignals obtained from these sensors. Central to the MHPMS is a concept of the health *Body Area Network* (BAN). The health BAN is defined as *a network of communicating devices worn on, around or in the body which provide mobile health services to the user* [Jone09]. The MHPMS BAN consists of the following: 1) A number of sensors capturing patient's biosignals; 2) A device called *Mobi* to which these sensors are connected using wires. The Mobi is also capable of connecting to the Bluetooth network; and 3) A *Mobile Base Unit* (MBU) which is a handheld capable of connecting to the Mobi and wireless network. The MBU may have GPS capabilities depending on its model. Within a BAN, sensors and Mobi together form a *sensor system*. The BAN sensor system is capable of configuring multiple types of sensors. One example of the MHPMS BAN shown in [Jone09] is reproduced in Figure 2.7. A functional architecture of the MHPMS adapted from [Halt04] is shown in Figure 2.8. In this figure, dotted rectangles indicate physical location where the parts of MHPMS are executed. Rounded rectangles correspond to the functional layers of the architecture.

[13] The MobiHealth project was supported by Commission of the European Union in the frame of the 5th research Framework under project number IST-2001-36006.

Figure 2.7: An example of MHPMS body area network (reproduced from [Jones09])

A sensor system is capable of sampling patient's physiological signals at various frequencies (e.g. 128, 256 Hz) [Kons04]. There is a communication channel associated with each type of biosignals, over which respective biosignals data is transmitted to the MBU. The MBU uses wireless Internet connectivity to transmit this data to the *Back-End System* (BESys) hosted at the location of the healthcare provider. Communication between the entities within a BAN is referred to as *intra-BAN communication*. A sensor system can be interfaced and managed from the MBU using an intra-BAN interfacing and management software. Such communication is facilitated by the connectivity offered by *intra-BAN communication provider*. The communication between the BAN and the BESys is referred as *extra-BAN communication*.

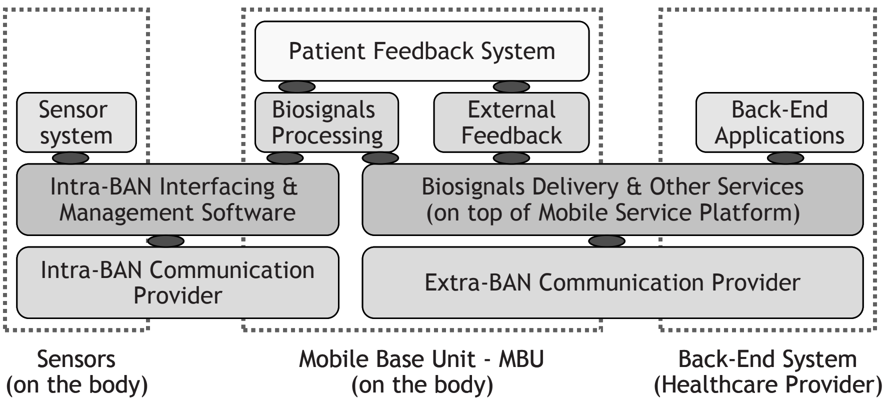

Figure 2.8: Functional architecture of the MobiHealth patient monitoring system

A *biosignals processing* unit performs a number of operations on the biosignals obtained from the sensor system before sending them for transmission. A local feedback can be provided to the patient in terms of a GUI which shows the biosignals measurements (e.g. heart-rate) on the MBU. The delivery of biosignals uses *monitoring device service* which is a MBU counterpart of *monitoring service* (a nomadic mobile service developed on the principles of MSP described in Section 2.4). The communication between MBU and BESys is supported by MSP by using a wireless Internet connectivity offered by the *extra-BAN communication provider*. BESys applications can perform a number of tasks, e.g. real-time viewing of biosignals at the healthcare center.

The monitoring service is based on the principles of nomadic mobile service and consists of two components: 1) *monitoring device service* on the MBU; and 2) *monitoring surrogate* in the fixed network. The monitoring device service and its surrogate communicate with each other via MSP. The part of MSP on the MBU is referred to as MSP-IO. The monitoring surrogate resides at the surrogate host and it registers monitoring service with the Jini lookup service. The monitoring service relays patient's biosignals to an interested client, e.g. to the healthcare professional for their real-time display. The components of MHPMS used in biosignals processing are as follows:

- *Body Area Network (BAN) sensor set*: A MHPMS BAN sensor set processes biosignals measured by sensors attached to the patient's body, and outputs multiple channels of biosignals data. Every biosignal is transmitted over an associated channel.
- *Biosignals Profile:* A *biosignals profile* consists of particulars about the biosignals to be sent to the health-care professionals. These include name of the channel associated with a particular biosignal, sampling frequency of a biosignal and length in bytes of the biosignal data. This profile varies in accordance with the biosignals to be collected. The biosignals received from the BAN sensor set are filtered according to the specifications in the biosignals profile and later aggregated in a one-second time interval. The monitoring device service consists of service buffer which maintains the number of packets waiting to be processed by the MSP-IO. This number is mapped to the *fill level* (0 - 100) of this buffer. The buffer stores the biosignals data up to a predefined number of seconds (configured to approx. 60 seconds for the experimentation) till those are transmitted by MSP-IO. An example of a biosignals profile is shown in Figure 2.9.
- *Filter*: As the name suggests, this component filters biosignals received from the sensor system according to the specifications in the biosignals profile.
- *Aggregator*: This component aggregates biosignals over a certain time interval into biosignal packets and sends them to the buffer. Irrespective of their delivery to the BESys, the biosignals packets are always stored in the MBU (e.g. in the memory card).
- *Buffer*: The buffer temporarily stores biosignals packets before they are read by MSP-IO for their transmission to BESys. This *cyclic buffer* maintains the number of packets awaiting processing by MSP-IO and when the total size of these packets

exceeds a certain configurable *threshold* value, older biosignals packets are removed from the buffer to accommodate newer biosignals packets. It is to be noted that within the MHPMS, the biosignal packets are always stored locally on the MBU (e.g. in the flash memory card) irrespective of the state of cyclic buffer.


```
<ChannelSet ID="Plain-0050">
<Device Type="org.mobihealth.sensormodel.impl.btswinmobi" ID="0924030028"
Config="00:A0:96:1D:87:1F" BaseFrequency="1024" Frequency="128">
<Channel Name="ExG1" ByteLength="3" Active="true" />
<Channel Name="ExG2" ByteLength="3" Active="true" />
<Channel Name="ExG3" ByteLength="3" Active="true" />
<Channel Name="ExG4" ByteLength="3" Active="true" />
 <Channel Name="Temp" ByteLength="3" Active="false" />
<Channel Name="SaO2" ByteLength="1" />
<Channel Name="Pleth" ByteLength="1" />
<Channel Name="PulseRate" ByteLength="1" />
<Channel Name="SensorStatus" ByteLength="1" Active="true" />
<Channel Name="Digi" ByteLength="1" />
<Channel Name="SawTooth" ByteLength="1" />
<Channel Name="TMSIstuffing" ByteLength="1" Active="false" />
</Device>
```


Figure 2.9: An example of a biosignals profile

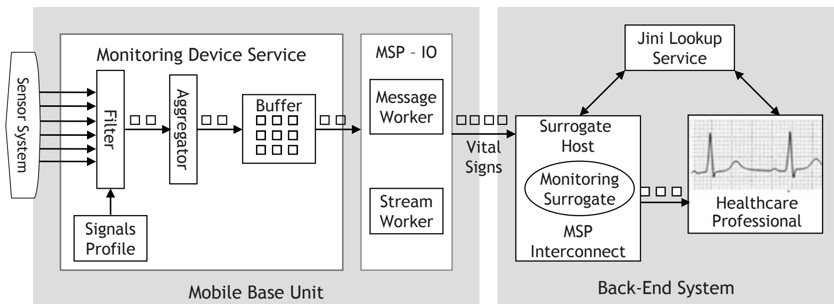

Figure 2.10: Biosignals processing and delivery components

- *Message worker*: The message worker component of MSP-IO is responsible for receiving *one-way* and *request-reply* messages from the monitoring device service (surrogate) and sends them to its surrogate (device service, respectively). MSP-IO additionally uses message worker to send MBU service lifecycle messages and MSP control messages (e.g. *keep-alive message*) to the surrogate host.
- *Stream worker:* The stream worker component of MSP-IO provides a buffer (within MSP-IO) to which a monitoring device service constantly writes streaming data that contains biosignals. The stream worker opens a connection to the monitoring surrogate via selected network interface, reads biosignals data from the buffer and

transmits this data to the surrogate host. A wireless ISP typically assigns an IP address to the MBU network interface dynamically at the establishment of the wireless connection (e.g. GPRS) [Rekh96], which is used by the *stream worker* and *message worker* as the transport end-point for opening a communication to the surrogate host. The surrogate host is identifiable using a *global IP address* or *URL*.

2.7 Assumptions

Both of the areas E-Health and mobile computing are developing rapidly in the last decade. The availability of miniature non-invasive sensors, body implants capable of communication using wireless technologies, availability of mobile devices capable of performing complex calculations and their ability to communicate with the Internet are making it possible to realize the vision of providing ubiquitous health care.

These days a few of the network operators provide integrated 2.5G/3G (GPRS/UMTS) communication services. An integrated GPRS/UMTS system uses UMTS network for the applications which need high bandwidth. Wherever UMTS is not available, GPRS is used for the data communication [Chen08]. Compared to 2.5G/3G networks (e.g. GPRS/UMTS), the 3.5G and 4G WWAN networks (e.g. HSDPA and LTE) provide higher bandwidth. Traditionally, the wireless networks offer lower bandwidth in comparison to the fixed network. However, bandwidth savvy network centric Internet applications (e.g. video-on-demand) are consuming the fixed network bandwidth heavily. Since wireless networks are evolving in the capacity, certain users may experience the situation in which the wireless networks offer higher bandwidth compared to the fixed networks.

Considering the evolution of the wireless network technologies, the work reported in this thesis assumes that though the wireless network technologies evolve, it is unlikely that one technology will replace all the existing technologies. Thus multiple network technologies will continue to exist with each other. In this thesis, the context-aware handover experiments reported in Chapter 4 and Chapter 5 consider two types of wireless networks, namely GPRS and 802.11b. However, these mechanisms are not limited only to the GPRS and 802.11b technologies. Irrespective of the wireless network technology, the network selection mechanism in Chapter 4 considers the link capacity of the wireless networks, while the network selection mechanism proposed in Chapter 5 considers QoS offered by the wireless networks.

For the experiments reported in Chapter 4 and Chapter 5, the maximum goodput requirement for the biosignals transmission is 36 kbps. If the high bandwidth wireless networks are widely deployed, one may argue that if a patient doesn't travel beyond the coverage area of a wireless network then the handover functionality is not required. However, there is a common trend that as the network bandwidth capacity increases; the bandwidth requirements of networked applications increase in proportion. E.g. in the future, the patient monitoring applications may use high quality mobile video conferencing between a patient and a healthcare professional.

The bandwidth requirement for a TV quality digital video (30 frames/sec) is 27.7 MBps [Furh94], which is a magnitude higher than the biosignals considered in our experiments. This analogy combined with the existence of multiple network technologies suggests that there will be a need for the vertical handover mechanisms for selecting suitable network for the data transmission.

Data compression techniques e.g. deflate compression [Deut96] are used in MHPMS to reduce the amount of data being transmitted. The performance evaluation of the MobiHealth patient monitoring system conducted in [Wac04a] showed that for the biosignals data packet of size 3800 bytes, the deflate compression algorithm achieves on an average 51.86% reduction. However, the size of compressed data increases with increase in the variability of measured biosignals [Wac09a]. The assessment of deflate compression algorithm for the compression of the IP packets consisting of randomly generated data [Mcgr00] showed only 0.01% reduction for the packets of size 1 KB. No compression was achieved for higher packet size. Since the exact correlation between the biosignals packet size and the deflate compression ratio is unknown [Wac04a], in the experiments reported in this thesis, the compression functionality is not considered.

2.8 Conclusions

This chapter provides a number of concepts, terms and architectural considerations which are referred in further chapters. In the process, we have identified the place of mobile patient monitoring in the entire E-Health domain. We also outlined a number of concepts related to several computing paradigms e.g. service oriented computing and context-aware computing. A concise description of the MobiHealth Patient Monitoring System (MHPMS) is provided and its architectural foundations are also discussed. Certain important concepts/definitions introduced in this chapter are as follows:

M-Health is an appliance of mobile computing, wireless communications and network technologies to deliver or enhance diverse healthcare services and functions in which at least one stakeholder (such as patient, doctor or caregiver) has a freedom to be mobile, maybe within a limited area.

Mobile patient monitoring is the continuous or frequent measurement and analysis of the biosignals of a mobile patient from a distance by employing mobile computing and wireless communication technologies.

The QoS is a performance of the data delivery service offered by a network communication path. This performance is measured in terms of the QoS characteristics. The QoS characteristics we focus on are *goodput*, *round trip time* and *data loss ratio*.

A *nomadic mobile service* is a service oriented computing based service offered by the Internet capable mobile host such as a handheld device, mobile phone or an embedded device which publishes this service in the service registry so that the client located anywhere in the Internet is able to find and bind to it. A nomadic mobile service may also act like a *nomadic mobile context source* that offers three types of interfaces to the client: *getContext*, *subscribeContext* and *unsubscribeContext*.

The assumptions considered during the research period of this thesis are as follows:

1. To support certain healthcare related tasks, continuous transmission of the biosignals to the back-end system is necessary.
2. Though the wireless network technologies evolve, it is unlikely that one technology will replace all the existing technologies. Thus multiple network technologies will continue to exist with each other. There will always be a need for the vertical handover mechanisms to support complete geographic mobility of a patient.
3. There is a common computing trend that as the network bandwidth capacity increases; the bandwidth requirements of the networked applications increase in proportion. Hence, there will always be need for mechanisms to provide optimal QoS to the mobile patient monitoring systems.
4. Since the exact correlation between the biosignals packet size and the compression ratio is unknown, the compression functionality is not considered in the conducted experiments.

Chapter 3

State of the Art

This chapter presents state of the art of three research areas: *mobile patient monitoring systems*, *vertical handover approaches*, and *QoS predictions*. The mobile devices are used in the mobile patient monitoring system to exploit their immediate presence with the patient for the acquisition and delivery of the health related data. Depending on application requirements, available technology choices and research expertise, a number of mobile patient monitoring systems are in use these days. Similarly, a number of vertical handover approaches are reported in the scientific literature. Among these, we selected six mobile patient monitoring systems and six vertical handover approaches to include in this state of the art.

This chapter is organized as follows: The state of the art of mobile patient monitoring systems is presented in Section 3.1. Section 3.2 is on the vertical handover approaches. An overview of QoS predictions is presented in Section 3.3. Section 3.4 presents conclusions of the chapter.

3.1 Mobile Patient Monitoring Systems

The vision of *pervasive healthcare* outlined in [Vars07] aims at providing healthcare to anyone, anytime, and anywhere by removing geographical, temporal and other limitations while increasing both the coverage and quality (of the pervasive healthcare systems). The scientific literature is rich with reports on M-Health systems and mobile patient monitoring systems which contribute greatly towards achieving the vision of pervasive healthcare. A brief overview and potential benefits of M-Health systems are presented in [Patt02], wherein successful case studies in the area of *electronic patient records*, *emergency telemedicine*, *tele-radiology* and *home monitoring* are discussed. An overview of M-Health systems with a focus on handling emergency situations and providing emergency services is provided in [Kyri07]. A comprehensive survey of ubiquitous computing for the remote cardiac patient monitoring is presented in [Kuma08]; wherein the architecture of a number of wireless cardiac monitoring systems and QoS characteristics of the underlying platforms are discussed.

The IBM Corporation has developed a multi-purpose device named as *personal mobile hub* [Huse04] which supports wireless protocols such as Bluetooth, ZigBee and 802.11. The personal mobile hub also functions as a gateway for the transmission of biosignals. A number of developments in the M-Health domain are compiled in a book on the emerging mobile health systems [Iste05].

Provided that a number of mobile patient monitoring systems exist, selecting a few of them to include in this state of the art was a daunting task. The criteria we use for their selection are manifold including diverse intra-BAN and extra-BAN communication techniques, evidence of practical trials and availability of sufficient published scientific information. Based on these criteria, we selected five mobile patient monitoring systems [Ango00, Gao07, Gay07, Lin04, and Wai08] along with the MHPMS to include in this chapter. In Section 3.1.1, we present a generic architecture of mobile patient monitoring systems and elaborate the criteria used for comparison. Section 3.1.2 provides an overview of selected mobile patient monitoring systems. Section 3.1.3 provides an overview of selected systems.

3.1.1 Generic Architecture of a Mobile Patient Monitoring System

A generic architecture of a mobile patient monitoring system based on architectures of the mobile patient monitoring systems [Ango00, Gao07, Gay07, Halt04, Lin04, Sata00 and Wai08] and related work in this area [Jone09] is shown in Figure 3.1.

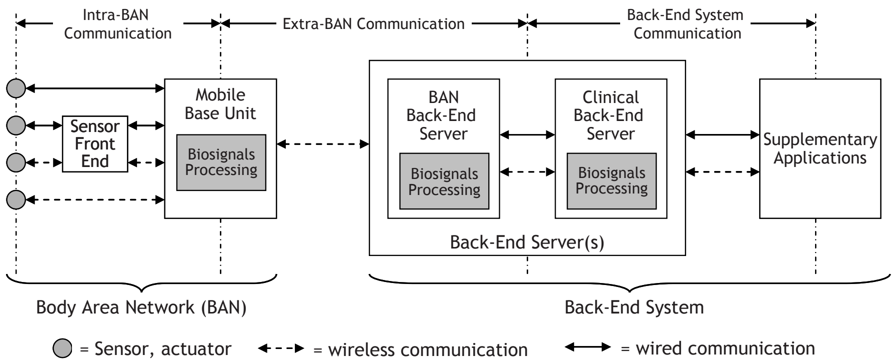

Figure 3.1: A generic architecture of a mobile patient monitoring system

In this architecture, a mobile patient monitoring system is seen as a set comprising of a *Body Area Network* (BAN) and a *Back-End System* (BESys). The BAN is defined as a network of communicating devices worn on, around or within the body which is used to acquire health related data and to provide mobile health services to the patient. Intra-BAN communication may be wired, wireless or a mixture of the two. The BAN consists of a *Mobile Base Unit* (MBU) and a set of BAN devices [Jone09]. The BAN devices may be sensors, actuators or other wearable devices used for medical purposes. We distinguish between two types of BAN devices: *invasive* and *non-invasive*. Invasive devices are inserted in the living body by incision or by insertion of some instrument, while non-invasive devices do not infiltrate the body and do not involve any invasive medical procedure.

The sensors may directly transmit biosignals data to the MBU or do it so via the *Sensor Front-End* (SFE) using either wired or wireless connectivity. An example of SFE is a *Mobi* device used in MHPMS (Section 2.6). The SFE may also digitize and filter raw analogue biosignals before transmitting them to the MBU. The biosignals may be processed locally within the BAN and/or remotely in the BESys. The MBU acts as a communication gateway for transmitting biosignals. The communication within the BAN and BESys is referred as *extra-BAN communication*. In line with the definition of mobile patient monitoring presented in Chapter 2, the extra-BAN communication must be supported by a wireless link.

The BESys comprises of the *back-end server(s)* and supplementary applications which make use of biosignals being received and possibly stored at these servers. The back-end servers are of two types: *BAN back-end server* to which the MBU transmits biosignals data and *clinical back-end server* [Jone09] which may host custom healthcare applications e.g. determining caregiver nearest to the patient's location. These two servers may be collocated with each other constituting a single back-end server. The communication within the elements of BESys is referred as the *back-end system communication*. Based on the generic architecture shown in Figure 3.1 and the scope of this thesis, we came up with the criteria shown in Table 3.1 to describe the selected mobile patient monitoring systems.

Table 3.1: Parameters for describing the mobile patient monitoring systems

Parameter	Description
Architecture	An architecture of a selected mobile patient monitoring system in relation to the generic architecture shown in Figure 3.1
Sensor/Actuator set	Types of sensors/actuators used in the selected system
Sensor front end	Details of the sensor front end in terms of its make/model, included features and supported biosignals processing
MBU	Features of MBU, supported applications, network interfaces and biosignals processing details
Intra-BAN communication	• Communication type (wired/wireless) for sending biosignals from the sensors to the MBU • Biosignals processing along the communication path and on the MBU • Biosignals delivery QoS requirements • Communication protocol used for biosignals delivery
Extra-BAN communication	• Communication techniques for delivering biosignals from the MBU to the BESys

	• Biosignals processing along the extra-BAN communication path and on the BESys • Biosignals delivery QoS requirements • Communication protocol used for biosignals delivery
BAN back-end server and supplementary applications	• BAN back-end server information such as technology choices for its implementation and deployment • Supplementary applications which use biosignals and other health related data available at the BAN back-end server
Clinical back-end server and supplementary applications	• Clinical back-end server information such as technology choices for its implementation and deployment • Supplementary applications which use biosignals and other health related data available at the clinical back-end server
Back-end system communication	Communication protocols and technology choices for delivering biosignals data from the BESys to the supplementary applications
Trial patient group	Types of patients for which the selected mobile patient monitoring system is developed
Trial information	Information about trials conducted to validate selected mobile patient monitoring system with a focus on the number of patients and duration of the trial
Reported findings/problems	Information about significant technical findings and problems reported during the trial
Challenges addressed and contribution	Summary of significant challenges addressed, major contribution of the selected system to the pervasive healthcare area

3.1.2 Overview of Selected Mobile Patient Monitoring Systems

Based on our selection criteria which are evidence of practical trials, target patient group, innovative intra-BAN and extra-BAN communication techniques and availability of sufficient published information, we selected following five mobile patient monitoring systems for comparison with the MHPMS:

1) *Yale-NASA Himalayan climbers monitoring system* developed by NASA and Yale university (hereon referred as *Yale-NASA system*) [Ango00, Sata00];
2) The *Advanced Health and Disaster Aid Network (AID-N) system* developed collaboratively by a number of institutions including John Hopkins University, University of California, Harvard University and others (hereon referred as *AID-N system*) [Gao07];
3) *Personalized Health Monitoring (PHM) system* developed by the University of Technology, Sydney (hereon referred as *PHM system*) [Gay07];
4) *A wireless-PDA based physiological monitoring system* developed at the National Taiwan University in cooperation with the National Taiwan University Hospital (hereon referred as *NTU system*) [Lin04];

5) *A wireless Continence Management System (CMS)* for the patients suffering from dementia developed by the Institute for Infocomm Research, Singapore in cooperation with other partners (hereon referred as *CMS System*) [Wai08].

Furthermore, to be consistent with the terms and concepts introduced in Chapter 2, we stick to the term 'mobile patient monitoring system' for all the above approaches.

Yale-NASA mobile patient monitoring system

To determine the reliability of mobile patient monitoring systems in the extreme environments, the Yale–NASA team organized the *Everest Extreme Expeditions* (E3) during the spring Himalayan climbing seasons in the years 1998 and 1999. The E3 was focused on two aspects: *humanitarian* (providing medical support) and *scientific* (conducting medical and technology research).

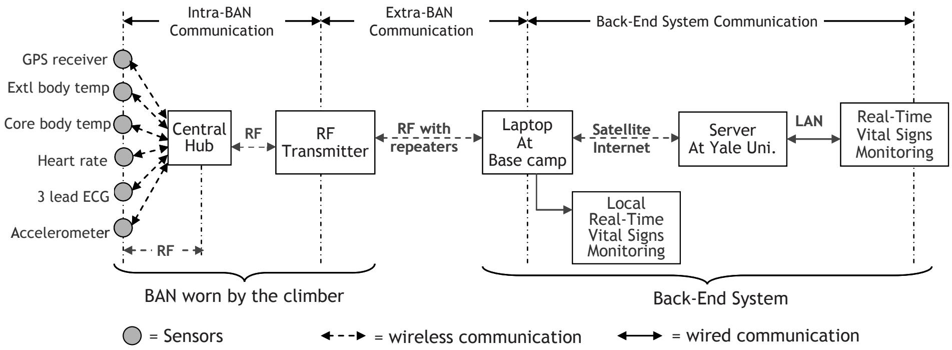

Figure 3.2: Architecture of the Yale-NASA mobile patient monitoring system

Along with providing medical care for the *Everest Base Camp* community; the Yale-NASA team also performed real-time monitoring of selected climbers. The architecture of Yale-NASA system is shown in Figure 3.2 and a number of features of this system are described in Table 3.2.

Table 3.2: Features of the Yale-NASA mobile patient monitoring system

Parameter	Description
Sensor set	• Non-invasive sensors for measuring heart rate, 3-lead ECG, body surface temperature monitor, core body temperature pill • Accelerometer (for gross body motion and activity) • GPS system for position tracking
Sensor front end	• A central processing hub with RF capabilities and supporting maximum of 16 sensors per person • Capable of storing and forwarding biosignals data

	• Biosignals data is transformed or encoded into ASCII format
MBU	RF transmitter
IntraBAN communication	• *Sensor to SFE*: Personal Wireless local area network with digital RF signals, sensors queried 4 times per minute, SFE stores data for 5-minutes before transmission to MBU • *SFE to MBU*: RF communication
ExtraBAN communication	• RF 918 MHz link with one repeater station to facilitate vectored path for the RF signal transfer • Max *115 kbps* bandwidth • Biosignals bandwidth requirement: *2.4 kbps*
BAN back-end server and supplementary applications	• Laptop at the Mt. Everest base camp • Aggregates received ASCII datasets every 5 minutes • Features GUI for biosignals display
Clinical back-end server and supplementary applications	• Server at the Yale university • Biosignals monitoring • Features GUI for biosignals display
Back-end system communication	• 64 kbps satellite Internet link – *2.4 kbps* used • *TCP/IP protocol* for the transfer of ASCII data
Trial patient group	High altitude climbers
Trial information	• Real-time monitoring of 3 climbers • Duration > 45 minutes
Reported findings/problems	• 95% - 100% sensors functioning • Rate of biosignals transmission loss from 3% to 12% • No biosignals were lost for more than 20 minutes or 4 consecutive recordings

The novelty of Yale-NASA system as described in [Sata00, Ango00] is that this is the first ever reported mobile patient monitoring system in truly remote or hazardous conditions and at the high altitude. The system proved to be robust, fault tolerant and easily monitored through the graphical interface. The ratio of biosignals transmission loss ranged from 3% to 12%. Such loss may be possible because of the severe weather conditions; however the effect of such conditions on signal transmission were not determined. On several occasions, there was a lack of signal acquisition (95% - 100% sensors functioning). However, a frequent sampling (every 15 seconds) provided adequate compensation during the period of momentarily loss. This exercise indicates that the transmission modes such as *low earth-orbiting satellites* (LEOS) may prove effective to monitor people in remote areas. Use of LEOS helps to eliminate need for RF repeaters and numerous technicians.

AID-N mobile patient monitoring system

In the emergency medical situations such as those involving disasters, a critical first step in the response process is a rapid and accurate triage of the patients. The triage refers to the sorting of patients according to an urgency of their need for the medical intervention. During an emergency response, triage information is communicated and continuously updated to multiple parties of the response team. AID-N system described in [Gao07] is proposed as an electronic alternative to the traditional paper tag or colored ribbon based triage system. Herewith, we consider the AID-N system trial during a mass casualty disaster drill as elaborated in [Gao07]. In the drill exercise described in [Gao07], the usability of AID-N system is compared with the traditional paper tag based triage system. The architecture of AID-N system is shown in Figure 3.3 and a number of features of this system are described in Table 3.3.

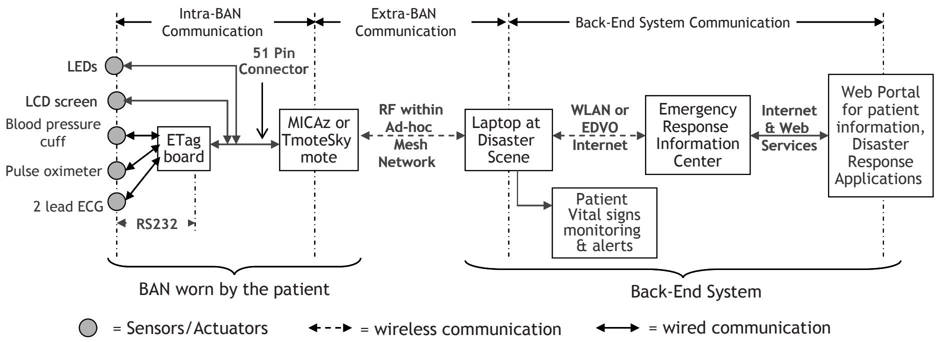

Figure 3.3: Architecture of the AID-N mobile patient monitoring system

Table 3.3: Features of the AID-N mobile patient monitoring system

Parameter	Description
Sensor/Actuator set	• Non-invasive sensors for measuring heart rate, 2-lead ECG, pulse rate, oxygen saturation, blood pressure • LEDs signifying triage class of a patient • LCD displaying oxygen saturation and heart rate
Sensor front end	• Specially designed ETag sensor board • RS232 – DB9 connector for connecting sensors • Interfaced with MICAz mote with 51-pin expansion connector
MBU	• MICAz or Tmote Sky mote • Bulitin IEEE 802.15.4 radio transceiver • 51-pin expansion connector with D/A interface for connecting to the

	SFE • ECG amplification, filtering and sampling • Algorithm for extracting heart-rate • Indoor radio range: 20–30 m • Outdoor radio range with substitute IEEE 802.11 antennas: 23-66 m
IntraBAN communication	• *Sensor to SFE*: Serial communication using RS232 standard, BP readings every 5 minutes • *SFE to MBU*: Using the 51-pin connector • *MBU to Actuators*: LED management over 4-bit data bus • 128 bytes needed for the ECG waveform
ExtraBAN communication	• Ad Hoc mesh network constituted by the MBUs using RF 2.4 GHz frequency based on the CodeBlue wireless sensor network • Spanning tree for each BAN back-end server covering all the assigned MBUs • Max *250 kbps* bandwidth • 1 byte needed for heart rate, 128 bytes for ECG waveform
BAN back-end server and supplementary applications	• Laptop at the disaster scene • Biosignals analysis algorithms • Features GUI for biosignals and triage display • WLAN and EVDO PC card network interfaces
Clinical back-end server and supplementary applications	• Central server known as *Emergency Response Information Center* • Information sharing with other systems like web portal • Web Services for providing patient and triage information • Coordinating response activities at the disaster site using PDAs
Back-end system communication	• WLAN connectivity preferred • Alternately, transfer over EDVO – CDMA 1x-data network
Trial patient group	Patients at the disaster scene
Trial information	• 20 patients, one incident commander, treatment officer, transport officer, triage officer each, three response team members • Use of pulse oximeter and 2-lead ECG sensors
Reported findings/problems	• High ECG data rate caused serious delays while running several motes in parallel • Coverage problems due to a patient wandering out of range of other patients and line of site problems • Suitable mechanism for location tracking is needed

The novelty of AID-N system as described in [Gao07] is that the use of electronic system allows first emergency responders to retriage three times higher number of patients than the first responders using paper tags. AID-N approach increases quality and quantity of patient care during disaster situations. There were several challenges reported during the implementation and deployment of AID-N system. Firstly, during the disaster situations, indoor location tracking capability with minimal setup time and a resolution of one meter accuracy is a challenging issue. Secondly, high data rate of ECG waveforms causes serious delays while running several motes in parallel in an ad-hoc mesh network. Thirdly, RF coverage problem due to patient wandering and out of line of site communication is found to be another challenging issue.

PHM mobile patient monitoring system

Cardiovascular diseases are a leading cause of mortality in developed countries. The PHM system [Gay07] is specially targeted at patients who have a suspected cardiovascular disease and need to be monitored round the clock. One of the main features of PHM system is the use of off-the-shelf sensor systems with a built-in sensor front end. This allows a PHM system user just to have a mobile device with the *Microsoft Windows Mobile OS* and to buy or rent required sensors. A patient downloads required software onto the mobile device and uses it just like any other windows mobile application. The architecture of PHM system is shown in Figure 3.4 and a number of features of this system are described in Table 3.4.

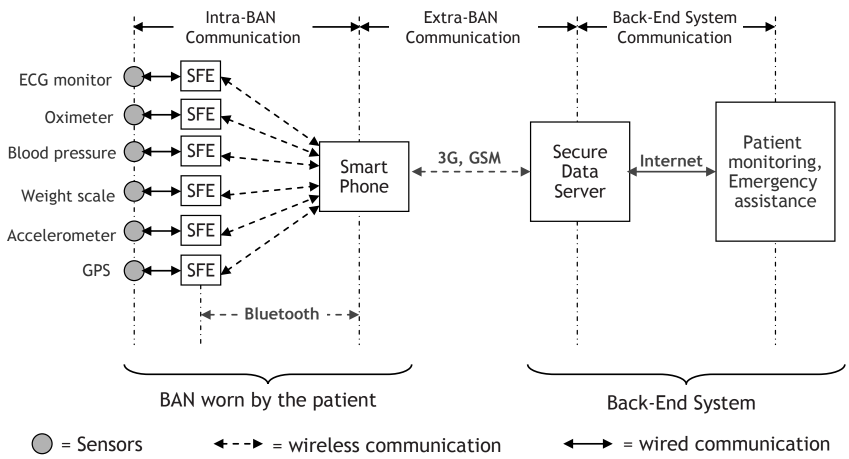

Figure 3.4: Architecture of the PHM mobile patient monitoring system

Table 3.4: Features of the PHM mobile patient monitoring system

Parameter	Description
Sensor set	• Of-the-shelf and non-invasive sensor systems • 1 channel ECG monitor, oximeter, blood pressure, weight scale, internal/external GPS, accelerometer • All external sensors with Bluetooth capabilities
Sensor front end	Subcomponent of of-the-shelf sensor system incorporating embedded software for signal processing
MBU	• Any smart phone running Microsoft Windows Mobile OS

	• Biosignals analysis algorithms
IntraBAN communication	• *Sensor to SFE*: custom wired communication • *SFE to MBU*: Bluetooth
ExtraBAN communication	Internet connection using 3G or GSM technologies
BAN/Clinical back-end server and supplementary applications	• Microsoft ASP .NET based server • Features GUI for biosignals display • Biosignals processing and storage • Patient monitoring and emergency services
Back-end system communication	Secured Internet connection
Trial patient group	Patients suffering with cardio-vascular diseases
Trial information	70 patients with low-medium risks
Reported findings/problems	• PHM BAN and application is easy for use to the patients • The data received by the healthcare professionals is of sufficient quality to identify cardio-vascular problems

The PHM system trial demonstrated that it is easy to use and in the majority of cases, biosignals received by the cardiologists were of sufficient quality to make a proper assessment. Another feature of the PHM system is that the healthcare professional can select one or more sensors to be used for a particular patient to provide personalized monitoring and treatment. The PHM system trials highlighted the need for personalized feedback. E.g., some of the patients would not like to interact much with the application, as they find it stressful. Elderly patients living alone would like to have audio reminders and warnings.

CMS mobile patient monitoring system

Incontinence refers to the inability to voluntarily control or manage the loss of urination or defecation. It is highly prevalent in the elderly population especially those suffering from dementia. The CMS system [Wai08] is targeted at the elderly dementia patients residing within the nursing home and suffering from incontinence. The BAN consists of receiver(s) associated with wetness detection sensor integrated into the MICAz mote platform mounted nearby the patient bed or wheel chair. In order to detect incontinence, the actual wetness sensor is inserted into the diaper which is worn by the patient all the time. The architecture of the CMS system is shown in Figure 3.5 and a number of features of this system are described in Table 3.5.

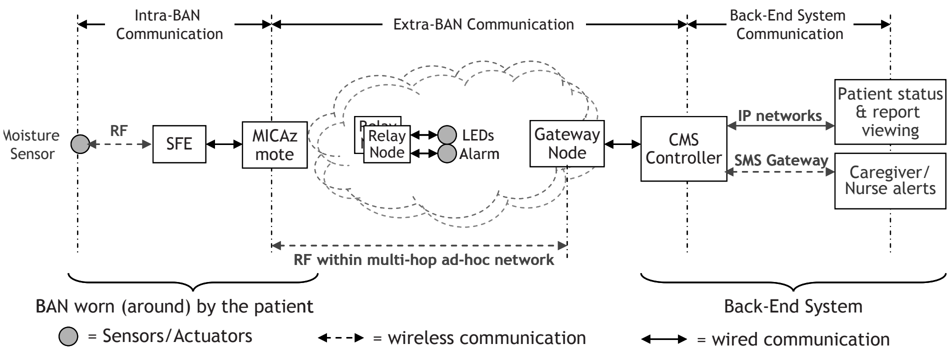

Figure 3.5: Architecture of the CMS mobile patient monitoring system

Table 3.5: Features of the CMS mobile patient monitoring system

Parameter	Description
Sensor/Actuator set	• Commercially available wetness detection sensor with RF communication capabilities • Actuators consists of LEDs and alarm for notification on the detection of wetness caused by either urine or feces • Actuators are integrated on the so called *relay nodes*
Sensor front end	• Subcomponent of the wetness sensor system especially RF receiver incorporating embedded software for signal processing • wetness sensor unit sends one-time moisture detection signal to the SFE upon occurrence of wetness
MBU	MICAz mote with 2.4 GHz RF communication capability – so called *sensor node*
IntraBAN communication	• *Sensor to SFE*: proprietary RF wireless communication • *SFE to MBU*: custom wired communication through one of digital hardware interfacing bus such as ADC, I2C, SPI, etc.
ExtraBAN communication	• Multi-hop wireless network using RF communication • Consists of relay cum actuator nodes and gateway node • MBU, *relay nodes* and *gateway node* communicate with each other wirelessly • Gateway node has wired connectivity such as Ethernet and Serial to the Back-End server
BAN/Clinical back-end server and supplementary applications	• *CMSController* incorporating Java based SOA modules • Caregiver/nurses SMS alerting through mobile phone via SMS gateway • Patient status monitoring and report viewing over the IP network
Back-end system	• Based on the principles of SOA

communication	• SMS gateway • IP network
Trial patient group	Elderly patients suffering from dementia and incontinence and wearing diaper all the time
Trial information	• Prototype trial with 1 patient over 2 weeks • In a nursing home • 2 relay nodes, 1 sensor node and 1 gateway node
Reported findings/problems	• No false alarms • Wetness detection rate of 50% attributed to deliberately reduced sensitivity of the moisture sensor, position of the sensor within a diaper and variable properties of different types of diapers • RF out-of-range problems due to the patient with wetness sensor wandering out of range of the sensor node

The novelty of the CMS system as described in [Wai08] is that it involves use of a scalable and extensible distributed sensor network to support potentially large deployment of wetness sensors in institutions such as nursing home and elderly care center. With the use of wireless sensor network, incontinence monitoring of the elderly can be performed either on the bed (inside the ward) or wheelchair (outside of the ward). The relay mechanism for patient's information transfer ensures that patients are free to move around in the nursing home. The trial of the CMS system reported no false alarms, however the wetness detection ratio was 50%. Such a low ratio is attributed to various reasons such as deliberately reduced sensitivity of the wetness sensor in order to eliminate false alarm rates, wrong placement of the sensor within a diaper and variable absorbance properties of different types of diapers. The trial also emphasized on RF out-of-coverage problems and need for training caregivers on proper handling of day to day system operations.

NTU mobile patient monitoring system

In the large hospitals, during the transport of a patient, (e.g. to the ICU or to the radiology room) it is required to transport bulky medical monitoring equipments along with patient's trolley. These bulky monitors and wires connecting them to sensor leads could result in problematic situations and inconvenience. NTU system [Lin04] is targeted as an alternative to the use of bulky medical monitoring equipments during the intra-hospital patient transport. NTU system makes use of advanced mobile technologies for continuous patient monitoring during intra-hospital transport. Along with the use of TCP/IP for error-free biosignals transmission, NTU system includes robust security features such as user authentication, secure wireless transmission and end-to-end *Advanced Encryption Standard* (AES) algorithm. Architecture of the NTU system is shown in Figure 3.6 and a number of features of this system are described in Table 3.6.

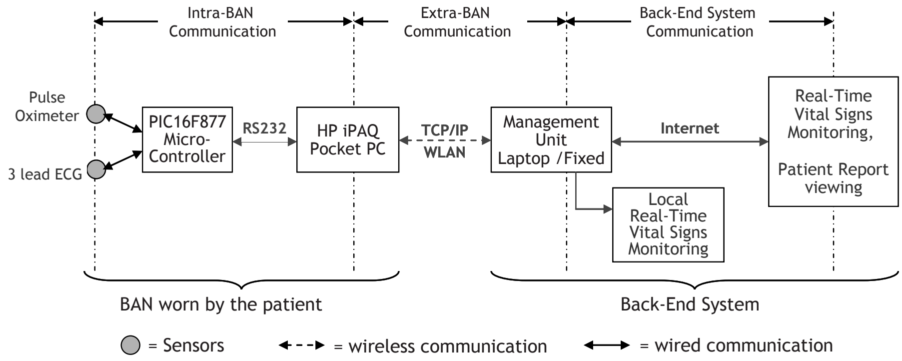

Figure 3.6: Architecture of the NTU mobile patient monitoring system

Table 3.6: Features of the NTU mobile patient monitoring system

Parameter	Description
Sensor set	Non-invasive sensors for measuring 3-lead ECG and pulse-oximeter
Sensor front end	• Based on 8-bit PIC16F877 microcontroller • ECG signals amplification, filtering and AD conversion • Processing of *photoplethysmograph* (PPG) signals to obtain pulse rate and oxygen saturation • Digitizes signals with 200Hz sampling frequency
MBU	• HP iPAQ Pocket PC H5450 with integrated WLAN • System program developed by Microsoft embedded visual C++ to display real-time waveforms, local data storage and alarm triggering • Capable of storing biosignals in the SD memory
IntraBAN communication	• *Sensor to SFE*: wired communication • *SFE to MBU*: Serial communication using RS232 standards, baud rate of 115.2 kb/s.
ExtraBAN communication	Data transfer over TCP/IP using WLAN connectivity
BAN/Clinical back-end server	• So called *Management Unit* • Laptop/fixed terminal running Windows 2000 OS and MySQL server • Biosignals display • Vitals signs transmission and patient reports transfer over the Internet for the interested clients
Back-end system communication	Internet connection using wired or wireless connectivity
Trial patient group	20 healthy patients at National Taiwan University Hospital
Trial information	• Trial run over one month, used by 30 doctors and 20 nurses • Transportation of the patient from the ICU to radiographic examination

	room
Reported findings/problems	• No errors reported in biosignals transmission • NTU system was rated as highly satisfactory • Outperforms traditional monitors system in terms of mobility and usability • No interference of NTU system detected with other electronic equipments used in ICU and radiographic examination

The distinguishing aspects of NTU system as illustrated in [Lin04] are that it improves portability of patient monitoring equipments during the intra-hospital transport of patients. The use of wireless connectivity increases the flexibility and usability of patient monitoring. The NTU system is found to be user-friendly, convenient and feasible for the intra-hospital patient transport. The improvements proposed in the NTU system include use of advanced algorithms for determining multiple health-related parameters using only a few sensors and replacement of the RS232 connection by Bluetooth for additional flexibility.

MHPMS mobile patient monitoring system

The motivation behind the development of the MHPMS system is that of *providing ubiquitous medical care*. Due to an ever-advancing miniaturization of sensor devices and computers as well as ubiquitous deployment of wireless Internet networks, patients will be able to send full, detailed and accurate biosignals measurements and receive medical care irrespective of where they are. As illustrated in Section 2.6, the MHPMS is firstly developed in the MobiHealth project (*http://www.mobihealth.org*). Other projects which use the MHPMS prototype for research and trials are HealthService 24 (*http://www.healthservice24.com*), AWARENESS (*http://awareness.freeband.nl*) and Myotel (*http://www.myotel.eu*). Instead of focusing on monitoring a particular type of disease, MHPMS has focused on developing a generic BAN which can be used for a particular type of treatment by using specific set of sensors and implementing appropriate application functionality. E.g., a BAN may have different sensors for patients suffering from high-risk pregnancy, trauma, and cardio-vascular diseases. For details of these variants, we refer to [Buij03]. The architecture of MHPMS system is shown in Figure 3.7 and a number of features of this system are described in Table 3.7.

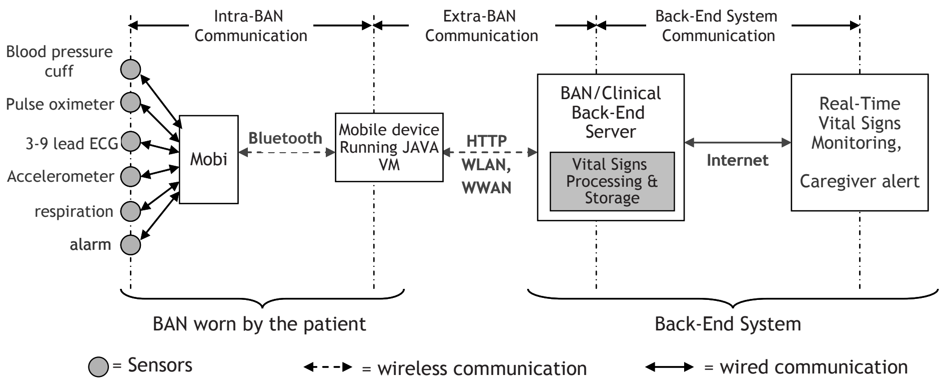

Figure 3.7: Architecture of the MHPMS mobile patient monitoring system

Table 3.7: Features of the MHPMS mobile patient monitoring system

Parameter	Description
Sensor set	• 3, 4 and 9 channel ECG, surface EMG, pulse oximeter, respiration sensor, temperature sensor, activity sensors (step-counter, 3D accelerometer) • GPS receiver
Sensor front end	• The SFE is called Mobi and it consists of 3/4/9 inputs for ECG, 1 auxiliary (AUX) input for either an activity or a respiration sensor, marker/alarm button input, pulse-oximeter (SaO2) input. • Capable of performing DSP programming computations for biosignals processing • Bluetooth serial port
MBU	• Implemented on various mobile phones and PDAs • Any mobile platform capable of running Java VM and RMI (Remote Method Invocation) • Bluetooth support • Application specific functionality and GUI running over generic BAN software layer and protocol stack.
IntraBAN communication	• *Sensor to SFE*: custom wired communication • *SFE to MBU*: Bluetooth
ExtraBAN communication	HTTP connection using WLAN/WWAN technologies
BAN/Clinical back-end server and supplementary applications	• Server with Jini surrogate host, Jini lookup service • Database for biosignals storage • Biosignals processing and display • Context-aware functionality for providing caregiver assistance in case of emergency

Back-End system communication	• Based on Jini RMI principles • A generic M-Health portal acts as a Jini client to access biosignals data from the Back-end server and displays them for viewing by the physician
Trial patient group	Low risk patients suffering from ventricular arrhythmia, high risk pregnancies, acute trauma, rheumatoid arthritis, mental health problems, COPD, elderly with co-morbidities including COPD and epilepsy.
Trial information	• 17 trial groups over 4 projects • Multi centre and multi-language international trials in Netherlands, Germany, Spain, Sweden and Cyprus
Reported findings/problems	• Technical failures such as system instability in the initial versions of MHPMS • Bandwidth problems and loss of network connectivity • Good acceptance from the end-users in the latest versions. E.g. continuous local biofeedback enables chronic pain patients to adapt their behavior rapidly and results in long lasting treatment effects

The MHPMS trials report positive experience working with healthcare organizations and clinicians. However, in the initial version of MHPMS system, technical failures (such as system instability), sub-optimal interface design and a difficult (re)start sequence caused irritation and confusion to users. Preliminary trials have shown the feasibility of using the system, but a number of problems were encountered. E.g. ambulatory patient monitoring is more successful for certain biosignals than others, because some measurements are severely disrupted by movement artefacts [Halt04]. The limited bandwidth provided by WWAN technologies is not sufficient for some applications which require monitoring many simultaneous signals per user. However, the latest results from the currently running Myotel project [Veld08, Voll08] which use MHPMS system indicate that continuous local biofeedback enables chronic pain patients to adapt their behavior rapidly and results in long lasting treatment effects. Adding the telemedicine dimension with feedback from the remote therapist further improves clinical outcomes related to pain and disability.

3.1.3 Overview of the Mobile Patient Monitoring Systems

Based on the features reported for the individual mobile patient monitoring systems Table 3.8 provides an overview of these systems in comparison to MHPMS for a number of criteria, the names of which are self-explanatory. Since maximum mobility is supported by employing wireless communication technologies, we provide a special emphasis on the wireless communication aspects of each selected system. This comparison table is based on the trials cited in respective research articles for each system. Hence even if a particular feature is present in the system, but is not reported, then it does not appear in Table 3.8.

Table 3.8: Overview of the selected mobile patient monitoring systems

Acronyms: BT -> Bluetooth, RF -> Radio Frequency

Parameter	Yale-NASA	AID-N	PHM	CMS	NTU	MHPMS
Supported num. of sensors	5	3	>6	1	2	>10
Sensors -> SFE comm.	RF	wired	wired	RF	wired	wired
SFE -> MBU comm.	RF	serial	BT	wired	serial	BT
MBU – V. signs display	no	yes	yes	no	yes	yes
MBU – V. signs storage	no	no	yes	no	yes	yes
Intra-BAN comm. problems	no	no	no	no	no	no
Extra-BAN comm. problems	no	yes	no	yes	No	yes
Extra-BAN comm. technology	RF	Multi-hop ad-hoc	3G, GSM	Multi-hop ad-hoc	WLAN	WLAN, 3G, GPRS
Extra-BAN comm. protocol	SMAC	SMAC	TCP/IP	SMAC	TCP/IP	HTTP
BESys comm. technology	TCP/IP	Web services	Web services	IP	HTTP	Jini
Geographic area of trials	outdoor	indoor	indoor/ outdoor	indoor	Indoor	indoor/ outdoor
End-to-End security	no	no	no	no	Yes	no
Reported trial problems	yes	yes	no	yes	No	yes

By analyzing mobile patient monitoring systems presented in this chapter, the following can be observed. These systems are useful in the outdoor as well as indoor environments. The systems are user-friendly, convenient for both – patients and healthcare professionals and the trials of these systems have shown the feasibility of their acceptance in the day-to-day life. During the trials, it was observed that these systems help to reduce the response time of a treatment. A mobile patient monitoring system can be custom designed for treating a particular type of patient or it can be generic enough to cater patients suffering from multiple problems.

In all of the systems presented herewith, whenever required, the biosignals are delivered continuously from the MBU to the back-end system. In terms of the QoS requirements, the bandwidth requirements for the biosignals delivery are explicitly stated in a few of the systems [Ango00, Gao07, Lin04, Buij03], however the delay and jitter requirements are not explicitly considered anywhere. A handheld mobile device (mobile phone or PDA) is a commonly used device which functions as a MBU. Though, other types of wireless devices (e.g. wireless sensor node, RF transmitter) are also used as MBUs. In the systems where a handheld mobile device is used as a MBU, the biosignals are displayed on the MBU as well as biosignals are also stored locally on the MBU.

In the systems where point-to-point or ad-hoc networks provide an extra-BAN connectivity, SMAC is the preferred communication protocol. In the systems where the extra-BAN connectivity is provided by the WLAN or WWAN technologies, IP based communication protocols are used for biosignals delivery. The preferred technology choices for communication within the components of the back-end system are service oriented architecture technologies and web based technologies. The most common applications provided by the back-end system are displaying patient's biosignals, viewing patient's report, providing emergency assistance to the patient and alerting a healthcare professional.

During the trials of these systems, certain problems were reported. The wireless network problems refer to the lack of sufficient bandwidth for the transmission of signals, high delay and unavailability of sufficient wireless network coverage. Hence a vertical handover support is necessary in the mobile patient monitoring systems to address these problems. Along with the efforts to ensure that the QoS requirements for the biosignals delivery are properly elicited and met by the extra-BAN communication path, it is also necessary to develop end-to-end security solutions along the entire biosignals transmission path. In these cases, an additional biosignals transmission delay resulting from the impact of user/network authentication needs to be taken into account. To make sure that the healthcare professionals have access to the high quality biosignals, the mechanisms to eliminate loss of biosignals during their delivery are necessary.

3.2 Vertical Handover Mechanisms

The term vertical handover refers to a switchover from one network connection to another for the exchange of data. For the multi-homed mobile devices, it is a common practice to use vertical handover technique to select one of the available wireless Internet networks and use the selected network for data transfer to and from the mobile device. The patient mobility may result in sudden disconnection from the wireless network in use by the multi-homed mobile device. In this case also vertical handover technique can be applied to select the other available wireless network. Section 3.2.1 describes a handover management process and vertical handover typology. Section 3.2.2 provides an overview of selected vertical handover approaches and illustrates parameters for their description. Section 3.2.3 describes in brief each of the selected approaches and Section 3.2.4 presents an overview of all the approaches.

3.2.1 Handover Management Process and Vertical Handover Typology

The need for vertical handover is motivated by so called *Always Best Connected* (ABC) concept, which refers to being connected in the best possible way in an environment of multiple wireless networks [Kass08]. The ABC concept can be realized using the *handover management* process [Kass08] that refers to selecting appropriate time to initiate handover and selecting the most suitable wireless network to maintain wireless connectivity. A handover management process is composed of following three phases [Kass08]: 1) *Handover information gathering* phase collects information required to identify a need for handover and initiate the handover; 2) *Handover decision making (network selection)* phase determines a suitable network for handover execution; and 3) *Handover execution* phase performs an actual handover to the network selected in the second phase. These three steps are shown in Figure 3.8.

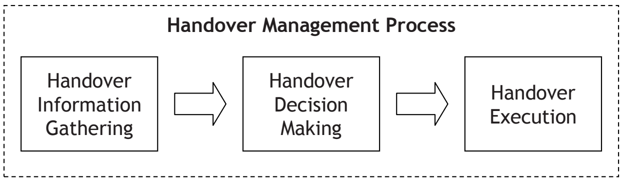

Figure 3.8: The steps in the handover management process

The information which can be identified to take a handover decision is grouped by [Kass08] into the following four categories: 1) *Network related* information includes parameters such as wireless network coverage, offered QoS, *received signal strength* (RSS) and security level; 2) *Terminal (handheld) related* parameters include velocity, battery power and location information; 3) *User related* parameters are user profile and preferences; and 4) *Service (application) related* parameters include QoS requirements. A comprehensive overview of the vertical handover decision strategies is also provided in [Kass08]. These strategies are grouped into following five types, namely, *decision function based*, *user-centric*, *multiple attribute decision based*, *fuzzy logic/neural networks based* and *context aware*. A comparison of these strategies based on the survey of a number of handover approaches indicates that for the handover decision making, a context-aware strategy takes into account multiple criteria, has high consideration of user preferences, is highly efficient, flexible and involves medium implementation complexity. Moreover, it supports applications which exchange data continuously and non-continuously.

A number of multiple attribute based decision making algorithms are compared in [Stev06]. These include *multiplicative exponent weighting* (MEW), *simple additive weighting* (SAW), *technique for order preference by similarity to ideal solution* (TOPSIS) and *analytic hierarchy process combined with grey relational analysis* (AHP+GRA). The AHP [Saat90] decomposes a network selection problem into several sub-problems and assigns a weight value for each sub-problem. This step is followed by the GRA to rank available networks and select the one with the highest ranking. All of these algorithms allow a number of handover information parameters to be included for handover decision making. The data traffic classes considered in [Stev06] are: *conversational* (e.g. voice traffic), *streaming* (e.g. streaming video), *interactive* (e.g. web browsing) and *background* (e.g. email) [Dixi01]. A simulation based comparison of decision making algorithms in [Stev06] shows that MEW, SAW and TOPSIS provide similar performance for all the four traffic classes above, while AHP+GRA provides a slightly higher bandwidth and lower delay for interactive and background traffic classes.

In the research literature, vertical handovers are classified depending on the location of entity that makes a vertical handover decision and the entity which executes the taken decision [Zdar04]. If the handover decision is taken by a mobile device, it is known as a *Mobile-Initiated HandOver* (MIHO). If the handover decision is taken by a network, then it is referred to as a *Network-Initiated HandOver* (NIHO). At times, the handover decision is based on information from both the network and the mobile device. If the decision is taken by a network based on information obtained from a mobile device, the handover is called a *Mobile-Assisted HandOver* (MAHO). In contrast, if the decision is taken by a mobile device based on information obtained from a network, it is called a *Network-Assisted Hand-Over* (NAHO). In the handover execution phase, if a network executes and controls the handover management process then it is referred as a *Network-Controlled HandOver* (NCHO). In contrast, if a mobile device executes and controls handover management process then it is known as *Mobile-Controlled HandOver* (MCHO).

Depending on the number of networks a mobile device is connected to at the time of handover execution, the handover management process is classified into various types [Kass08]. In the *hard handover*, a mobile device is connected to one network at a time. It is also known as *break before make handover*. In the *soft handover*, during the handover execution phase, a mobile device is connected to more than one network. Hence, it is also referred as *make before break handover*. A *seamless handover* is the handover where a transition to a new network is transparent to the mobile application.

There is certain latency involved in between the need for handover is determined and the time when handover is executed. Three phases involved in this process are named as *handover detection*, *handover triggering* and *handover execution* respectively [Bern04]. Handover latency is a sum of delays involved in these phases. *Handover detection delay* refers to the delay between an occurrence of a particular event in the system and the notification reporting this event. *Handover triggering delay* is attributed to the time taken by a handover decision making process to determine a suitable network for handover execution. *Handover execution delay* is attributed to the time elapsed in between the handover decision is made and the new network is used.

3.2.2 Overview of Selected Vertical Handover Approaches

Since a vertical handover technique is a promising approach to achieve the *Always Best Connected* vision, significant amount of research is reported in this area. The criteria we used to select a few of them for comparison include availability of sufficient published information, evidence of real-life trials or extensive simulations and a variety of handover information gathering, decision making and execution techniques.

A generic architecture of these approaches is based on the handover management process steps shown in Figure 3.8. Important features relevant to these approaches are summarized in Table 3.9.

Table 3.9: Important features of the vertical handover approaches

Parameter	Description
Target applications	Applications on a mobile device targeted by the handover scheme
Networks	Considered network technologies (e.g. WLAN, GPRS) for the handover
Handover parameters	List of handover parameters used in decision making classified according to the network, terminal, user and service related parameters
Origin of handover information	Where does handover information originates from (e.g. mobile device and/or network)
Information collection interval	Whether the information is obtained one-time or collected periodically
Handover trigger	What determines a need for the vertical handover
Handover decision technique	Technique applied for taking a handover decision and where it is executed
Handover execution technique	How a handover decision is applied for connecting to a selected network
Setup for practical/simulation based validation	System setup for the practical/simulation based validation of the handover approach
Results obtained from the practical/simulation based validation	Results obtained from the practical/simulation based validation of the handover approach
Major problems identified/lessons learned/contribution	Unique aspects of the scheme Major problems addressed and Contribution of the proposed approach

The approaches selected to include in this state of the art are as follows:

1) A context-aware computing based vertical handover mechanism targeted for multimedia applications in pervasive systems proposed at the University of Queensland, Australia (hereon referred as *Queensland approach*) [Bala04];
2) A context-aware computing based vertical handover mechanism proposed by researchers at the BenQ mobile in cooperation with the University of Klagenfurt, Austria (hereon referred as *BenQ approach*) [Ahme06];

3) A multi-attribute decision making based vertical handover function to support IEEE media-independent handover mechanism (hereon referred as *media-independent approach*) [Wu09];
4) A profile based vertical handover approach which uses application, user and network profiles during the handover management process (hereon referred as *profile-based approach*) [Hong06];
5) An *active application oriented* handover scheme which treats applications running on the mobile device as a main vertical handover decision criterion (hereon referred as *application-oriented approach*) [Chen05];
6) A vertical handover middleware named PROTON that uses policy-based decision making during the handover management process (hereon referred as *PROTON approach*) [Chak04];

Queensland Vertical Handover Approach

The Queensland approach to vertical handover [Bala04] is targeted at multimedia applications for dynamically redirecting incoming application data streams to a different network interface on a mobile device. If the QoS requirements of streaming application are not satisfied by the current network, then the Queensland system evaluates available networks for their ability to provide required QoS. If none of the available networks fulfils QoS requirements, then certain adaptations are done to minimize QoS violation. To determine QoS requirements of an application, user perceived QoS is mapped onto the network QoS indices. The vertical handover aspect of the Queensland approach is unique because it considers a combination of networks and devices to stream multimedia content. This means depending on the user location, the most suitable device and network combination is determined. The objectives considered during the handover decision making process for achieving this combined functionality are:

Objective 1: Maximize user's device preferences.

Objective 2: Maximize application bandwidth.

Objective 3: Minimize jitter, delay and loss.

Objective 4: Minimize bandwidth fluctuations.

The Queensland approach falls into the *network controlled handover* (NCHO) category. A handover management process of the Queensland approach is shown in Figure 3.9. A number of handover management parameters and their description are provided in Table 3.10.

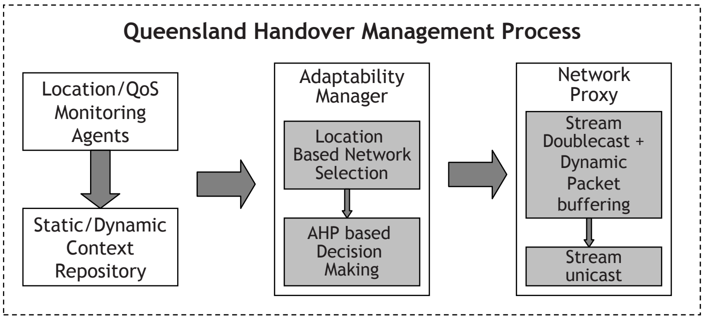

Figure 3.9: Main components of the Queensland handover management process

Table 3.10: Important features of the Queensland handover management process

Parameter	Description
Target applications and handover level	• Conversational streaming applications, e.g. real-time multimedia like live radio, video • Handover above the transport layer
Networks	Ethernet, WLAN, GSM, UMTS
Special entities supporting handover	• *Domain Name Cluster* (DNC) – multiple networks within a domain e.g. enterprise, departmental • *Context Repository* per DNC gathers, manages and evaluates context information • *Adaptability Manager* per DNC makes decisions about adaptations to context changes and handover decision • *Proxy* in every network is responsible for executing handovers. During handover, proxies *doublecast* a stream and provide dynamic packet buffering • *Location/QoS monitoring agents* provide notifications about users entering/leaving an area of network coverage and about QoS changes
Handover information	• *Network related:* coverage (grid map), proxy location, IP address, current QoS – bandwidth, loss ratio, delay and jitter. • *Terminal related:* memory, CPU, screen size, network interfaces, content capability, operating system, location. • *User related:* user perceptibility input, device priority, network priority • *Application related:* QoS requirements
Information collection interval	Context information is classified into two types: • *Static*: (e.g. device capabilities) collected less frequently • *Dynamic*: (e.g. user location, current network QoS) collected frequently
Handover trigger	• Application initialization or user changes device • User moves out of the network coverage area • User enters coverage area of the new network

	• Changes in the current network QoS • Changes in the alternative networks QoS
Handover decision technique	• Select a set of networks based on the user location • Determine suitable network which meets user QoS requirements • Use of the *Analytic Hierarchy Process* for decision making
Handover execution technique	• Old proxy triggers double-casting to the new proxy and mobile device • Once new proxy starts receiving streaming packets, streaming from the old proxy is stopped
Setup for practical validation	• Streaming JPEG RTP video using a *Java Media Framework* (JMF) • Network proxies implemented using JMF • GPRS, WLAN and Ethernet networks • PC and laptop as devices
Major problems identified/lessons learned/contribution	• Queensland approach uses a wide range of context information about networks, users, user devices and user applications • It provides adaptations to variety of context changes which are applicable to the static or mobile users. • Since ordinary users are not able to express communication QoS requirements in terms of network indices, an application QoS is specified as user perceived QoS.

BenQ Vertical Handover Approach

The BenQ approach for vertical handover [Ahme06] is aimed at five types of applications: *conversational voice*, *real-time streaming*, *interactive*, *non-real-time streaming* and *background*. The QoS requirements for these applications are stated in the *3GPP Technical Specification on the Services and Service Capabilities* [3GPP99]. A motivating argument behind the BenQ approach is that the handover decision should not solely rely on the received signal strength of the wireless network, but consideration of the *user preferences* is also necessary to take a handover decision. The user preferences are grouped into three types: *interface preferences*, *application preferences* and *objective preferences*. Instead of obtaining user preferences as discrete values, they are modeled as user-friendly options labeled with suitable *literals* which a user arranges in the descending order of priority. The objective preferences stated below are used by AHP algorithm for decision making.

Objective 1: Consider user's interface priority.

Objective 2: Minimize cost.

Objective 3: Maximize mean throughput.

Objective 4, 5 & 6: Minimize delay, jitter and *bit error rate* (BER) respectively.

The BenQ approach is in the *network assisted handover* (NAHO) category, as the *current QoS* information required to evaluate optimization objectives is obtained from the wireless network. The handover management process of the BenQ approach is shown in Figure 3.10. A number of handover management parameters and their description are provided in Table 3.11.

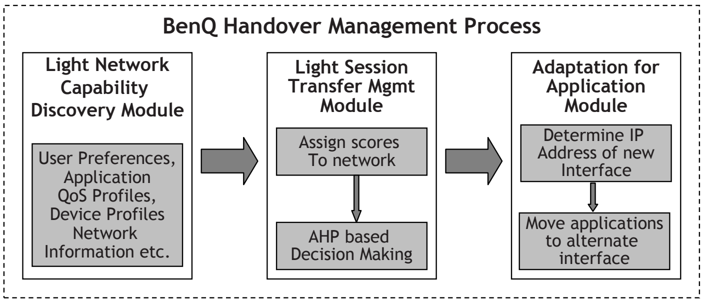

Figure 3.10: Main components of the BenQ handover management process

Table 3.11: Important features of the BenQ handover management process

Parameter	Description
Target applications and handover level	• Voice applications, real-time streaming, interactive, non-real time streaming, background • Handover above transport layer
Networks	Ethernet, WLAN, GSM, UMTS
Special entities supporting handover	• *Light Network Capability Discovery* (LNCD) module – monitors network interfaces, obtain network context • *Light Session Transfer Management* (LSTM) module – responsible for the handover decision making • *Adaptation for Application* (AfA) module – responsible for the handover execution
Handover information	• *Network related*: current QoS, network ID • *Terminal related*: screen resolution, battery life, processor speed • *User related*: network interface preferences, application type preferences, cost constraints • *Application related*: application type, QoS requirements e.g. bandwidth requirements for the conversational voice 4-25 kb/s [3GPP99]
Information collection interval	Periodic collection of the current QoS from reachable networks
Handover trigger	New network detected in the vicinity of a mobile device
Handover decision technique	• Decision is taken on the mobile device • Determine set of available networks • Assign scores to the available networks • Use *Analytic Hierarchy Process* for network selection
Handover execution technique	• Determine IP address of the selected interface • Move applications to use the new IP address (session re-establishment)

Setup for experimental validation	• Web browsing application (*interactive type*) called *AFAWeb* • Pocket PC running Windows Mobile 5.0 with GPRS and WiFi interfaces • Three optimization objectives: 1) minimize cost, 2) consider interface priority, and 3) maximize quality • One WiFi router and GPRS Internet • WiFi on/off during experiments
Major problems identified/lessons learned/contribution	• Higher detection time for WiFi network • Small average decision making delay (10ms) • Practically feasible scheme considering overall less (*GPRS->WiFi 60ms*, *WiFi->GPRS 20ms*) handover latency

Media-Independent Vertical Handover Approach

The media-independent approach for vertical handover [Wu09] proposes a handover decision engine for the IEEE 802.21 *media-independent handover* (MIH) functionality. The IEEE 802.21 is a standard to enable handover and interoperability between heterogeneous network types including 802.11, 802.16, 802.21 and non 802 networks such as 3GPP and 3GPP2 networks. The MIH QoS model defines QoS parameters mapping among these heterogeneous networks. A logical component called as *MIH Function* (MIHF) receives and transmits information about the configuration and condition of wireless networks around the mobile device. The MIHF can be located on the mobile device or in the network. As stated in the IEEE 802.21 MIH specification [IEEE09], the policies for handover and the algorithms for handover decision making do not fall within the scope of this standard. However, a component referred as the *media-independent information server* (MIIS) provides information including *access point SSID*, *operating mode* (e.g. *11g, 16e*) and *packet error rate* which is useful during the handover decision making. The MIH approach in [Wu09] fills in this gap by proposing a *multi-attribute decision making* (MADM) based *mobile controlled handover* (MCHO) scheme. The proposed scheme uses MIH services such as MIHF and MIIS to take a handover decision in the integrated WiFi and WiMAX networks. The proposed approach also uses AHP as a part of decision making for calculating weights of QoS parameters which are *priority*, *bandwidth*, *delay*, *packet error rate* and *jitter*. These parameters roughly correspond to QoS parameters defined in the IEEE 802.21, IEEE 802.11, IEEE 802.16 and 3GPP standards. The handover management process of the media-independent approach is shown in Figure 3.11. A number of handover management parameters and their description are provided in Table 3.12.

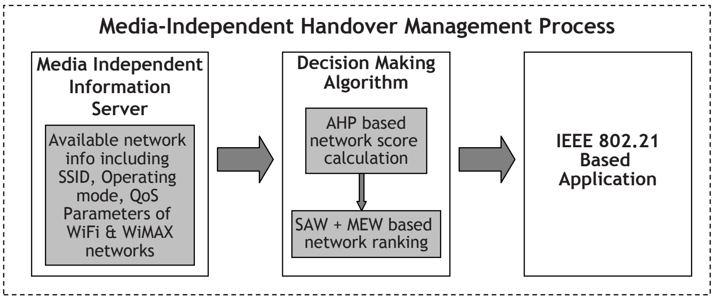

Figure 3.11: Main components of media-independent handover management process

Table 3.12: Important features of the media-independent handover management process

Parameter	Description
Target applications and handover level	• Four application traffic classes proposed in the IEEE 802.11e, IEEE 802.16e and 3GPP standards • Handover above Link layer
Networks	WiFi, WiMAX
Special entities supporting handover	*Media-independent information server* (MIIS) located in the IP network providing information including *access point SSID*, *operating mode* (e.g. *11g, 16e*) and *packet error rate*
Handover information	*Network related:* available network info including SSID, Operating mode, QoS parameters of the WiFi & WiMAX networks
Information collection interval	Periodic collection of the information from MIIS
Handover trigger	• *Current RSS* value less than preconfigured *RSS trigger* value • New access point detected
Handover decision technique	• Decision is taken on a mobile device • Use *Analytic Hierarchy Process* for assigning score to the available networks • Use SAW and MEW for ranking the networks

Handover execution technique	• The terminal registers with MIIS to become a MIH user through the *MIH Service Access Point* (SAP) interface. • The MIIS collects and provides the information services to all MIH users. • When link layer event happens, these registered users can obtain event notification from the MIH event trigger. • The mobile device receives status/information of the current wireless networks from MIIS and prepare for handover through MIH messages to initiate a decision engine. • The terminal's decision engine performs a decision making process to determine whether a handover is need. • If a handover is needed, the terminal sends relevant MIH commands.
Setup for simulation	• Heterogeneous mobile network where each WiMAX cell (3000m cell radius) overlays 9 Wi-Fi APs (100m cell radius) • Mobile devices follow *Poisson distribution* with an average speed of 5-30 m/s • *Random walk mobility* model • Comparison of simple *RSS based scheme*, *cost function based scheme* and proposed *MADM scheme using SAW and MEW* for 4 traffic classes
Major problems identified/lessons learned/contribution	• The proposed scheme provides smaller handover times and lower dropping rate compared to the RSS-based and cost function based decision making schemes.

Application-Oriented Vertical Handover Approach

The *application-oriented* vertical handover approach in [Chen05] allows a mobile device to choose the most suitable network depending on requirements of *application in use*. In this approach, it is proposed to switch off network interfaces on the mobile device when it is not in use for data transfer. The justification behind these choices is twofold: firstly, certain applications on the mobile device are best to run using a particular wireless network. E.g., GSM/GPRS is suitable for the voice applications. Secondly, in order to reduce power consumption on the mobile device, it is beneficial to switch off the unused network interfaces. Normally, it is necessary to keep all the network interfaces of a mobile device switched on to search for the wireless networks in its vicinity. The proposed approach emphasizes using the network information obtained from the so called *Location Service Server* (LSS). The LSS provides information such as *network coverage area*, *bandwidth* and *latency* of the available networks around a mobile device. It is assumed that the location of the mobile device is known by means of the positioning systems such as GPS.

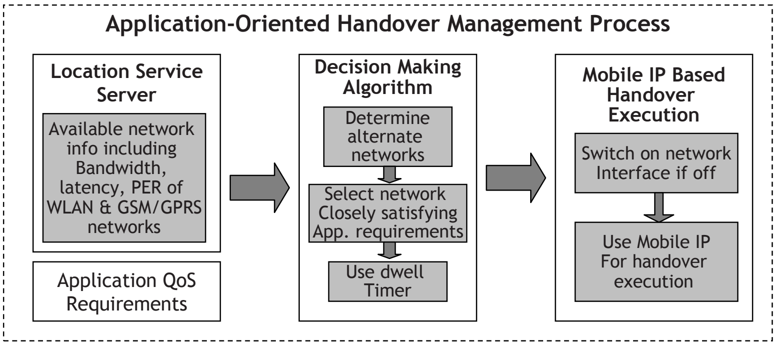

Figure 3.12: Main components of the application-oriented handover management process

The simulation experiments in [Chen05] compare two schemes: first, a *passive scheme* in which the LSS periodically sends information to a mobile device via the base station it is connected to; and second, the *active scheme* in which the mobile device requests information from LSS only when required. Though this scheme uses information made available by LSS, no details have been provided about the internals and functioning of LSS. The handover decision algorithm in [Chen05] is evaluated under two conditions: 1) mobile device boots up or changes the application it is using; and 2) RSS falls below a certain threshold level. During the decision making, to minimize the waste of resources available at the alternate network, the chosen alternate network is the one which provides just enough better QoS level for a given application. During the simulations, at any given time a mobile device is assumed to be in one of the following states: *stand-by mode*, *voice conversation* or *running real-time data-intensive applications* like video streaming. In this approach, unnecessary vertical handover refers to the handover from GSM to WLAN network when a mobile device is in the stand-by or voice conversation mode. Since the information obtained from LSS is used during decision making, the application-oriented handover approach is a *network assisted handover approach* (NAHO). The handover management process of the application-oriented approach is shown in Figure 3.12. A number of handover management parameters and their description are provided in Table 3.13.

Table 3.13: Important features of the application-oriented handover management process

Parameter	Description
Target applications and handover level	• *Stand-by* mobile device (req. bandwidth: 3–25 Kbps, latency: 10–500 ms, PER: 2-10%), *voice conversation* (9.6–64Kbps, 5–150ms, 2-10%), *video streaming* (50-500Kbps, 5–150ms, 2-8%) • Handover above IP layer using mobile IP
Networks	WiFi, GSM/GPRS

Special entities supporting handover	• *Location Service Server* (LSS) located in the Internet providing information about available networks' coverage, bandwidth, delay and PER
Handover information	• *Network related:* available networks' coverage, bandwidth, delay and PER • *Terminal related:* device mode, application in use • *Application related:* QoS requirements
Information collection interval	Mobile device requests network info from LSS if performance of the current network is not satisfactory
Handover trigger	• Mobile device boots up • Change of application in use • Signal strength of current network is weak
Handover decision technique	• Uses information received from LSS to select the network which closely satisfies application requirements • Start dwell timer to avoid ping-pong effect • If dwell conditions persist after timer expiry, perform handover
Handover execution technique	• Switch on network interface if off • Mobile IP based rerouting of the packets
Setup for simulation	• Mobile device with WLAN and GPRS interfaces, 1000 mAh battery capacity • 802.11b WLAN and Class 10 GPRS • 1 km square area with ubiquitous GPRS coverage, randomly placed WLAN hot-spots with 40m range • 50% standby mode, 30% voice conversation, 20% real-time streaming • Comparison of *passive* and *active* schemes
Major problems identified/lessons learned/contribution	• Active scheme reduces unnecessary number of vertical handovers, excessive interface on time and redundant network resource usage • Battery life of the device improves significantly by using LSS info. only to switch on the network interface when required

Profile-Based Vertical Handover Approach

The profile-based approach proposed in [Hong06] uses a number of specialized profiles called as *user's working profile* and *application profile* to take a vertical handover decision. Depending on the context information such as time of the day and corresponding user activities, a user may prefer to have certain applications running on a mobile device. E.g., *navigation* and *stock ticker* applications are useful for a particular user while driving to the work. Moreover, an application could run in multiple modes, e.g. a navigation application can run in the video based or audio based mode. Hence, in combination, the QoS requirements of an application are a factor of user's context and the application mode. The individual application requirements and user's preferences can be obtained using an *application profile* and *working profile* respectively, to form an *abstracted profile* which indicates generalized QoS requirement of applications running on a mobile device.

The QoS of available networks are evaluated against application requirements to take a vertical handover decision. The QoS values of application requirements and available networks are represented in lower and upper ranges. The normalization calculations are performed to compare required and offered QoS. The offered QoS is updated periodically, and a handover decision procedure is evaluated if QoS offered by a current network doesn't meet required QoS. In certain cases, a component named *application agent* changes an application mode to make the best use of selected network. In [Hong06], it is assumed that the network layer provides information about available networks and current network in use through a control channel. Since all the information required for handover decision making is obtained from the mobile device, the profile-based handover approach is a *mobile controlled handover* (MCHO) approach. The handover management process of profile-oriented approach is shown in Figure 3.13. A number of handover management parameters and their description are provided in Table 3.14.

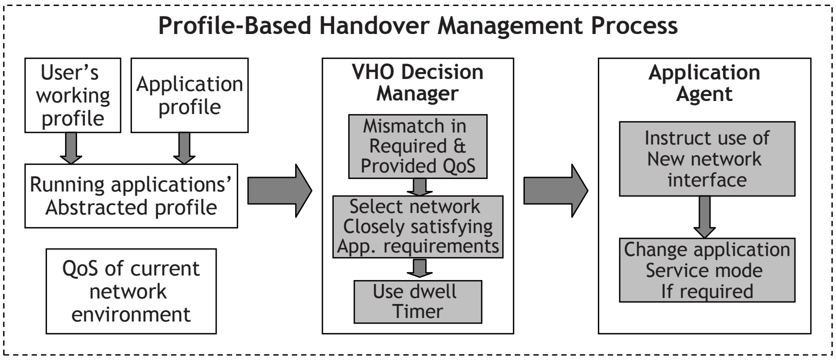

Figure 3.13: Main components of the profile-based handover management process

Table 3.14: Important features of the profile-based handover management process

Parameter	Description
Target applications and handover level	• Any mobile application the QoS requirements of which could be specified in terms of the required *bandwidth*, *packet error rate* and *latency* • Application level handover
Networks	• WiFi, GSM/GPRS
Special entities supporting handover	• *Working profile manager:* for managing a user's working profile • *Application manager:* for aggregating applications' QoS requirements and generation of the abstracted profile

	• *VHO decision manager:* compare abstracted profile with the current network information to take handover decision • *Application agent:* Manage application modes and request appropriate reconfigurations
Handover information	• *Network related:* available networks' QoS • *Terminal related:* available interfaces, application in use • *Application related:* QoS requirements, application modes
Information collection interval	• Periodic collection of the network related information from the network layer
Handover trigger	• Application QoS requirements could not be satisfied by the current network
Handover decision technique	• Perform normalization procedure periodically to compare *upper* and *lower bounds* of offered QoS and required QoS in three classes *-1*, *0* and *1*. • Handover decision is activated if the class of one of the upper or lower bounds is *-1*.
Handover execution technique	• Inform application agent about the decision • Application agent instructs use of new interface and changes application modes if required
Setup for simulation	• Mobile device with WLAN and GPRS interfaces • Three working patterns: *home -> office*, *office -> lunch* and *office -> home* • *Navigation*, *stock trade* and *stock information ticker* applications • Comparison of the *proposed scheme* with *single application based scheme* (like [Chen00]), *multi-application based scheme* and *service mode change enabled approach* • Comparison parameters include *accumulated throughput* and *application failures*
Major problems identified/lessons learned/contribution	• Simulation showed 130% throughput increase and 85% reduction in the application failures compared to *single* and *multi application* based schemes

PROTON Vertical Handover Approach

The PROTON vertical handover approach proposed in [Vida05] is a policy based solution for supporting vertical handover in the 4G networks. During the handover management process, PROTON follows an *event-condition-action* (ECA) paradigm where certain actions are taken depending on the occurrence of certain events those trigger the fulfillment of certain conditions. In PROTON, policies are the rules that specify actions to be performed in response to the predefined conditions triggered by certain events. One of the benefits of the policy based approach is that a number of policies could be added or removed as required and if there is any conflict between the policy rules, it is taken care by the *conflict resolution module*. However, a policy based system is usually complex and consists of a number of components such as *policy editor*, *policy repository* and *policy manager*. For this reason, the approach chosen by

PROTON is to host complex tasks of policy specifications, editing and preprocessing in the network side while the handover is executed on the mobile device (i.e. it is the policy enforcement point).

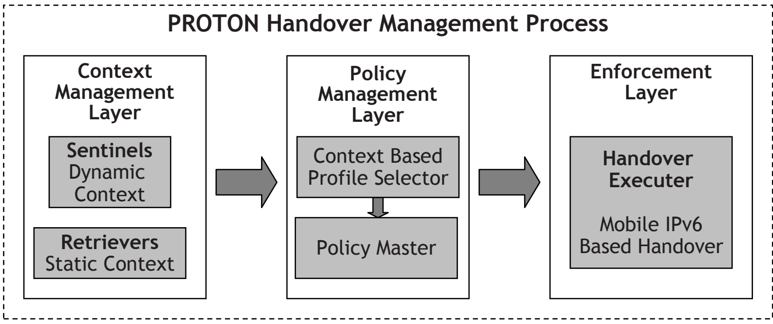

Figure 3.14: Main components of the PROTON handover management process

In [Vida05], a policy is represented using a special type of automata called as *Finite-State Transducer with Tautness Functions and identities* (TFFST). A set of TFFSTs is produced at the network side, and then deployed on the mobile device, where they are kept in a TFFST repository hosted at the *policy management layer*. In this layer, the component named as *context-based profile selector* uses events corresponding to a particular context to load a profile that defines a valid subset of policies to evaluate. E.g. if the speed of a mobile device is more than 90 km/h, then the active policies are only those that produce vertical handover as an action. One of the interesting features of the PROTON approach is that at higher velocities, fewer events are relevant for making decisions, decreasing the amount of processing. The component called as *policy master* is a decision point on the mobile device, which sends actions to be executed to the *handover executor*. The handover management process is executed entirely on the mobile device. Hence this approach falls under the *mobile controlled handover* (MCHO) category. The handover management process of the PROTON approach is shown in Figure 3.14. A number of handover management parameters and their description are provided in Table 3.15.

Table 3.15: Important features of the PROTON handover management process

Parameter	Description
Target applications and handover level	• Any mobile application the QoS requirements of which could be specified in terms of required *bandwidth*, *packet error rate* and *latency* • IP level handover
Networks	WLAN, GPRS, LAN
Special entities supporting handover	• *Sentinels*: For collecting dynamic context (e.g. velocity)

	• *Retrievers*: For collecting static context (e.g. application characteristics) • *TFFST repository*: Store a set of policies each of which is represented by the corresponding TFFST • *Context-based profile selector*: Select a valid subset of policies to evaluate, i.e., the appropriate TFFST depending on the context change • *Policy master*: Decide a set of policies to execute, the actions of which are sent for the policy enforcement • *Handover executer*: Execute Mobile IPv6 based vertical handover
Handover information	• *Network related:* network cross-layer information (physical, link and network layer characteristics), network traffic, nearby access points, signal strength • *Terminal related:* position, direction • *Application related:* application characteristics • *User related:* user profile
Information collection interval	Every context element has corresponding frequency of data collection
Handover trigger	Context changes lead to the selection of events which satisfy a particular condition on which the handover action could be taken
Handover decision technique	• Select a valid subset of policies to evaluate, i.e., an appropriate TFFST depending on the context change • Send actions for the execution to the handover executer
Handover execution technique	Mobile IPv6 based handover
Setup for simulation	• Mobile device with the WLAN, GPRS and LAN interfaces • Mobile IPv6 based WLAN-GPRS-LAN testbed • Indoor and outdoor location identification system • *Scenario based validation:* User disconnects laptop from LAN, connects to WLAN, later goes outdoor connecting to the GPRS, finally reaches restaurant and uses local WLAN • *Pedestrian*, *low speed* and *high speed* mobility profiles • Measurement of the *policy evaluation time* on the mobile device • Measurement of the Mobile IPv6 based *handover latency* (policy enforcement time) in terms of *detection time*, *configuration time* and *registration time*
Major problems identified/lessons learned/contribution	• Policy evaluation time *decreases* as the mobile device speed *increases* (attributed to generation of fewer events at the higher speed). *396ms* to *24ms* for *pedestrian* to *high speed* mobility profile • Mean handover latency: *WLAN->GPRS: 3806ms*, *GPRS->WLAN: 6897ms*, *LAN->GPRS: 4476ms*, *GPRS->LAN: 6525ms*

3.2.3 Overview of the Handover Management Approaches

An overview of the vertical handover management approaches is shown in Table 3.16. The parameter names are self-explanatory. This comparison table is based on the information available in the respective research articles for each approach.

Table 3.16: Overview of selected vertical handover management approaches

Parameter	*Bala04*	*Ahme06*	*Wu09*	*Chen05*	*Hong06*	*Vida05*
Handover level	Transport layer	Transport layer	Link layer	IP layer	Application layer	IP layer
Supported networks	LAN, WLAN, GSM, UMTS	LAN, WLAN, GSM, UMTS	WiFi, WiMAX	WLAN, GSM	WLAN, GSM	LAN, WLAN, GSM
Network information	Yes	Yes	Yes	Yes	Yes	Yes
Terminal information	Yes	Yes	No	Yes	Yes	Yes
User information	Yes	Yes	No	No	No	Yes
Application information	Yes	Yes	No	Yes	Yes	Yes
Decision algorithm	AHP	AHP	AHP + SAW/MEW	QoS comparison	QoS comparison	Policy based
Handover type	NCHO	NAHO	MCHO	NAHO	MCHO	MCHO
Practical validation	Yes	Yes	No	No	No	Yes

By analyzing information presented in Table 3.16, it can be observed that the vertical handover is performed at various levels of the OSI reference model. The MHPMS uses HTTP for the extra-BAN communication, which is an application layer protocol. The HTTP uses TCP connections for the transfer of data, which is a transport layer protocol. In the application layer and transport layer handover management approaches, the application information is mapped onto the QoS requirements to be fulfilled by the wireless network. The handover mechanisms referred above consider both, the WWAN and WLAN networks. The network QoS information is considered in all the approaches for taking a handover decision. The context-aware computing based approaches and the policy based approach consider all types of information for taking a handover decision. Among the cited approaches, three are three MCHO approaches, two NAHO approaches and one NCHO approach. The AHP algorithm and QoS comparison are commonly used decision making algorithms. The QoS optimization is one of the main objectives considered in the AHP algorithms used. Three of the handover approaches are evaluated using a practical setup while the other three are evaluated using simulations. The current QoS provided by the network is used during the decision making by four approaches [Bala04, Ahme06, Chen05 and Vida05]. Among these, the handover approach [Chen05] that is useful for reducing the power consumption of a mobile device is simulated, while the rest three are practically evaluated. However, in those approaches, minimizing power consumption is not an objective of the handover decision making process. In [Chen05], no details have been provided about determining the network QoS values.

3.3 Quality of Service Predictions

The performance of biosignals delivery from the MBU to the back-end system depends on QoS provided by the extra-BAN communication path. The *extra-BAN communication QoS* is bounded by QoS offered by a wireless network in use by the MBU. However, the real values of the offered QoS are unknown to the applications running on the MBU. This is because of the fact that public and private wireless access network providers often do not disclose detailed application level QoS-information. Instead the theoretical maximum bandwidth values and minimum delay values are often indicated. If a priori knowledge about the QoS offered by different wireless networks is available to the MBU, then the MBU can make a weighted decision about the selection of wireless network that best meets QoS requirements of biosignals delivery.

The research reported in [Wac09b] proposes an information system named as *Quality of Service Information System* (QoSIS) which is aimed at providing real-world QoS information consisting of QoS offered by different wireless networks in the vicinity of a mobile device. This information is named as QoS predictions. The QoS predictions contain information about following QoS parameters: *goodput* and *round trip time* (RTT). This information is provided in the following dimensions: *geographical location*, *time*, *wireless access network provider* and *wireless access technology*.

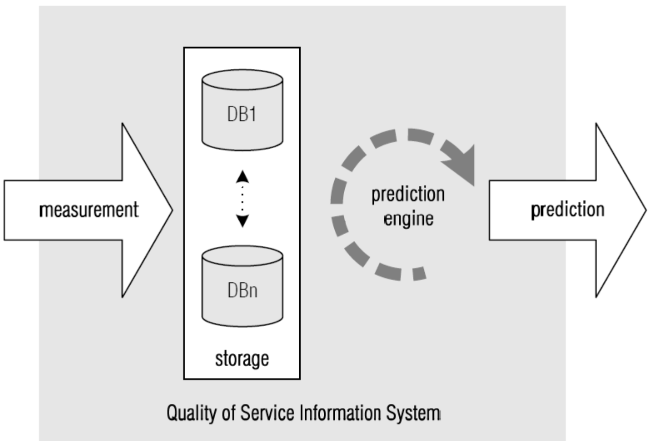

Figure 3.15: Functional blocks of the Quality of Service Information System [Wac09b]

To generate QoS predictions, the QoSIS applies machine learning algorithms onto the historic QoS information stored in a QoSIS database. The historic QoS information in the QoSIS database is contributed by a number of mobile devices in a collaborative information-sharing manner. A mobile device while using a wireless network submits data collected about observed QoS, selected *wireless network provider* (WNP) and technology information. This information is collected entirely at an application level on the mobile device. No information is obtained from the wireless network provider.

3.3.1 Quality of Service Information System Architecture

The QoSIS architecture described in [Wac09b] consists of following functional blocks: a) QoS measurement b) QoS-information storage; and c) QoS prediction. This architecture is shown in Figure 3.15.

The *QoS measurement function* periodically collects QoS-information contributed by mobile devices to the QoSIS, i.e., value(s) of QoS measures of interest, user location, time, WNP and wireless access network technology used. This function is implemented on a mobile device using either *passive QoS measurements* or *active QoS measurements*. In case of passive QoS measurements, an application such as mobile patient monitoring service is generating data to be sent to the surrogate host and a QoS measurement function measures QoS offered by a wireless network. In case of active QoS measurements, the data is generated in a controlled manner using applications such as netPerf[14] and QoS offered by the wireless network is measured.

The *QoS-information Storage function* aggregates and stores QoS information sent by the QoS measurement function. The QoS-information storage function may perform certain operations such as annotation, rating, sub-sampling or abstraction on the collected QoS information. This information is later used by a prediction engine which generates QoS predictions using certain machine learning algorithms.

The QoS prediction function disseminates QoS prediction information to an interested mobile device. The predictions are cached on a mobile device in the form of a prediction map which denotes user's current location and his nearby locations along with QoS predictions for these locations at different times. The prediction map is automatically updated by a mobile device either at regular time intervals or at the moment a user starts using his mobile service such as the mobile patient monitoring service. Due to the availability of cached QoS predictions, even when a user is out of the coverage of any wireless network, his mobile device can still determine (and inform the user) the location and QoS of the closest available wireless network.

[14] http://www.netperf.org/

3.3.2 Proof of Concept Results of the QoSIS Feasibility Experiments

The feasibility of deriving QoS predictions is evaluated for the QoS parameter *Keep-Alive RTT* during the use of *MobiHealth Patient Monitoring System (MHPMS)* for two MBUs. It is shown that for a given MBU the Keep-Alive RTT can be predicted based on its own measurement data or based on data collected by another MBU provided that the QoS is measured at the same location and time and using same wireless access network provider and technology. It is also feasible to predict the value of Keep-Alive RTT for one MBU, based on QoS data collected from both the MBUs. For further details on the QoSIS, its implementation, experimentation and results, we refer to [Wac09b].

The following representative empirical results are obtained from a comprehensive set of experiments reported in [Wac09b]:

1) It is feasible to derive accurate KA-RTT predictions for a device based on its own KA-RTT measurement data; for device 1 the mean accuracy is 80 % (± 18 %), while for device 2 it is 82 % (± 17 %).
2) It is feasible to derive accurate KA-RTT predictions for a device based on solely other device KA-RTT measurement data; KA-RTT predictions derived for device 1 based on device 2 KA-RTT measurement data have the mean accuracy of 78 % (± 20 %), while the other way around, mean accuracy is 79 % (± 21 %).
3) The most accurate predictions are obtained using the *J48 decision tree* machine learning algorithm.

3.4 Conclusions

This chapter presented state of the art of three research areas: *mobile patient monitoring systems*, *vertical handover approaches* and *QoS predictions*.

Mobile Patient Monitoring Systems

In this part, we illustrated a generic architecture of mobile patient monitoring systems and summarized six systems according to the following parameters: *sensor set*, *sensor front end*, *MBU*, *IntraBAN communication*, *ExtraBAN communication*, *back-end server*, *trials information* and *reported findings/problems*. All of the selected systems demonstrated promising results during their trials encouraging their use in real-life situations. However, during the trials of these systems, certain problems were reported. These problems and other observations are summarized as follows.

1. The wireless network problems refer to the lack of sufficient bandwidth for transmitting biosignals, high delay and unavailability of wireless network coverage.
2. Most of the existing patient monitoring systems lack necessary solutions to ensure end-to-end security of biosignals data. During the development of

such systems, additional biosignals transmission delay resulting from the impact of user/network authentication needs to be taken into account.

3. To make sure that the healthcare professionals have access to the high quality biosignals, the mechanisms to eliminate loss of biosignals during their transfer from the sensors to the back-end system are necessary.

Vertical Handover Approaches

In this part, we summarized and compared six vertical handover management approaches based on following parameters: *target applications*, *networks and handover level*, *handover information*, *handover decision and handover execution techniques*, *practical validation/simulation techniques*, and *major contribution*. The following is observed during this survey:

1. All of the selected handover approaches consider *network information* during handover decision making while *application requirements* and *mobile device information* are considered by the most of them. In addition to these, context-aware computing based approaches consider *user preferences* as additional information.
2. *Analytic Hierarchy Process* (AHP) based network ranking and *QoS based evaluation* are two of the mostly used decision making techniques.

Based on the study of these approaches, we have taken certain decisions in the subsequent chapters. These decisions and their justifications are presented herewith:

1. The architectures of MCHO mechanism (Chapter 5), NAHO mechanism (Chapter 6, Chapter 7) are based on the concepts of context-aware computing. Context-aware vertical handover mechanisms are used in [Bala04, Ahme06] for handheld mobile devices.
2. In the Queensland vertical handover approach [Bala04], to determine QoS requirements of an application, user perceived QoS is mapped onto the network QoS indices. We use similar approach to map the guidelines of healthcare professionals to the QoS requirements of biosignals delivery (Chapter 4).
3. A handover decision making technique used in the NAHO mechanism (Chapter 6, Chapter 7) makes use of AHP algorithm for selecting a wireless network. The use of AHP and selection of AHP optimization objectives is inspired from the handover approaches proposed in [Bala04, Ahme06 and Wu09].
4. In the vertical handover management process described in [Chen05], the wireless network QoS information provided by an entity named *Location Service Server* (LSS) is used to take a handover decision. Since the LSS is assumed to be located in the Internet, the vertical handover technique used in [Chen05] is classified as *network assisted vertical handover* [NAHO] approach. The *QoS Information Service* (QoSIS) [Wac09b] is an entity similar to LSS. The NAHO mechanism proposed in Chapter 6 is inspired from the use of LSS by vertical handover management process described in [Chen05].

5. During the handover decision making in NAHO mechanism (Chapter 6, Chapter 7), the chosen alternate network is the one which provides just enough better QoS for the biosignals delivery. This logic is inspired from [Chen05] which emphasizes on minimizing the waste of resources available at the alternate network.
6. The NAHO mechanism for reducing power consumption (Chapter 7) achieves so by switching off the unused network interfaces of the MBU. This part is also motivated from the application oriented handover approach described in [Chen05].
7. The NAHO mechanism uses a concept of *dwell timer* to avoid unnecessary handovers (Chapter 6). The use of dwell timer is also motivated from [Chen05].

QoS Predictions

In this part, we presented an overview of the QoS predictions [Wac09b]. The QoS predictions provide *goodput* and *round trip time* of wireless networks according to their *geographical location*, *time*, *wireless access network provider* and *wireless access technology*. These predictions are intended to provide a priori knowledge about QoS offered by different wireless networks to the MBU, so that the MBU can make a weighted decision about the selection of a wireless network.

The QoS predictions are intended to be provided by an information system named as *Quality of Service Information System* (QoSIS). The QoSIS described in [Wac09b] consists of following functional blocks: a) *QoS measurement;* b) *QoS-information storage*; and c) *QoS prediction*. The QoS measurement function hosted on a mobile device submits collected data about the observed QoS during their use of wireless network, selected wireless access network provider and technology to the QoS information storage function. The QoSIS applies machine learning algorithms onto the information stored by the QoS information storage function. The generated QoS predictions are disseminated to the interested mobile devices by the QoS predictions function.

Chapter 4

Requirements Elicitation

In this chapter, we elicit the following requirements: QoS requirements for mobile patient monitoring cases requiring continuous biosignals delivery; and vertical handover requirements. Eliciting QoS requirements addresses objective 1 of this thesis which is as follows: How to infer QoS requirements for the mobile patient monitoring cases requiring continuous biosignals delivery from the MBU to the back-end system? The elicitation of vertical handover requirements is necessary to address the rest of thesis objectives.

This chapter is organized as follows. Section 4.1 presents three mobile patient monitoring cases in which it is necessary to deliver biosignals continuously for a certain duration (depending on the purpose of patient monitoring application) from the MBU to the *back-end system* (BESys). In Section 4.2, we further analyze these cases to infer QoS requirements for biosignals delivery. It is to be noted that in the M-Health domain, we did not find any related work that deals with deriving QoS requirements of biosignals delivery. Section 4.3 illustrates handover information requirements for the proposed mechanisms. The conclusions are presented in Section 4.4.

4.1 Patient Monitoring Cases Requiring Continuous Biosignals Delivery

In certain type of mobile patient monitoring systems all the biosignals processing steps are implemented within the BAN. One example is the *Myofeedback system* [Veld08] described in Section 1.1.2. Another example is the *stress monitoring system* elaborated in [Jova03]. The BAN described in [Jova03] consists of the following: sensors measuring *heart-rate variability* (HRV), a device named *wireless heart rate monitor* that stores upto 60 hours of HRV data and the iPAQ PDA functioning as MBU. The operator periodically downloads stored biosignals data from the wireless heart rate monitor. For the patient monitoring cases described in [Veld08] and [Jova03], it is not necessary to continuously transmit biosignals from the MBU to the BESys. In this research, we consider mobile patient monitoring cases in which it is required to continuously transmit biosignals from the MBU to the BESys because the feedback of a healthcare professional is required to assess patient's current health condition. The other types of patient monitoring cases such as providing local feedback [Veld08] or store and download cases [Jova03] are excluded from this research. In the following, we present three examples of continuous biosignals delivery.

4.1.1 Detection of an Irregular ECG Pattern

A mobile patient monitoring system developed in the HEARTRONIC project [Roch08] aims at providing early warning of a heart stroke by continuously monitoring and analyzing patient's ECG. This system is intended to detect any heart anomaly in real time, send a warning to the responsible healthcare professional and transmit relevant biosignals data to the devices such as PC, PDA or smart phone. The HEARTRONIC BAN consists of the following: 8-lead ECG sensor array, *wearable processing unit* (WPU) for processing patient's ECG and a mobile device functioning as a MBU. The WPU obtains biosignals from the ECG leads at the sampling rate of 512Hz. The WPU provisions an algorithm to detect irregular ECG patterns. Once an irregular ECG pattern is detected, the WPU continuously transmits ECG data to the MBU. The MBU further transmits the ECG data and patient's location using wireless connectivity to the *HEARTRONIC application server*. On the reception of this information, the application server determines a healthcare professional to whom an alert is to be sent. The addressed person performs diagnosis using available ECG and patient's history. The action taken by the healthcare professional consists of the following: recognition of false alarm, call the patient or dispatch an ambulance to patient's location. In this example, the biosignals are continuously transmitted from the MBU to the BESys on the occurrence of an event which is the detection of an irregular ECG pattern.

4.1.2 Remote Physiotherapy Treatment

A mobile patient monitoring system presented in [Ferg09] aims at performing a physiotherapy treatment of a patient. During the physiotherapy session, the patient is located at home and patient's biosignals data is continuously transmitted using wireless connectivity to the remote healthcare center. In the system prototype described in [Ferg09], the BAN consists of multiple accelerometer sensors attached to the patient's body and a laptop that functions as a MBU. The accelerometer sensors together form an ad-hoc network. One of the sensors is automatically selected to act as a hub. All the sensors transmit acceleration values (biosignals) to the hub at the sampling rate of 1000Hz. The hub aggregates and samples acceleration values received from other sensors and afterwards these values are sent to the MBU. The acceleration values received at the MBU are stored locally. While a remote physiotherapy session is in progress, the acceleration values are transmitted using either WLAN or 3G connectivity to the site of a remote physiotherapist. At that site, the information being received is used to render body parts of a 3D image of a patient. As noted in [Ferg09], the difference between using acceleration values for the construction of a 3D image and using a webcam for the real image of a patient is that using the former approach, the exact numerical values for all aspects of patient's movement are recorded. The duration of a remote physiotherapy session varies per case. In this case, the acceleration values are continuously transmitted from the MBU to the BESys for the duration of a remote physiotherapy session as determined by the healthcare professional.

4.1.3 Trauma Patient Monitoring

Trauma is commonly defined as any severe or life-threatening injury. Frequently, trauma is a result of crash of a motor vehicle, fall, drowning, gunshot wound, fires and burns and similar sort of incidents. The *MobiHealth Patient Monitoring System* (MHPMS) [Halt04] has applications during the trauma situations. The trauma team consists of two types of members: onsite trauma team composed of paramedics and in-hospital trauma team composed of healthcare professionals such as surgeons. On the occurrence of a trauma event, the paramedics report to the trauma site with the trauma patient BANs. The trauma patient BAN consists of sensors for collecting *respiration*, *ECG, oxygen saturation* and *pulse rate* biosignals of a patient. These biosignals are collected at the sampling rate of 64Hz, 512Hz and 128Hz respectively [Buij03, Dima03]. The PDA functions as a MBU and transmits patient's biosignals continuously to the in-hospital trauma team [Alon02]. The in-hospital trauma team continuously analyses these biosignals to monitor the first possible treatment at the trauma scene. The patient is always monitored while being transported to the hospital. Based on the biosignals being received, the surgeon in the hospital determines whether there is a need for further diagnostics or surgery on the patient. Because of the continuous transmission of biosignals, it is possible to prepare operation room and equipments in advance so that the patient treatment begins with the minimum delay on the arrival at hospital.

4.2 QoS Requirements Analysis

The three examples presented in Section 4.1 need human (healthcare professionals) involvement in the decision making process. From the viewpoint of healthcare professionals, there are three basic requirements those need to be considered in these cases: 1) Certain types of biosignals are must for decision making; 2) The quality of biosignals being received should be at least good enough so that the decision making is not affected; 3) In case the decision taken expects a patient to take certain action, then the feedback of a healthcare professional should be received by a patient to allow a certain reaction time.

For the remote physiotherapy treatment example described in Section 4.1 the following specific requirements can be correlated respectively: 1) The acceleration data received from the accelerometer is necessary to render patient's movements in a 3D image; 2) The acceleration values received at the hospital should be good enough so that the physiotherapist can correlate movements in a 3D image to patient's actual movements; and 3) In case, the physiotherapist requires the patient to perform certain movements, then the patient should be able to receive these instructions in time, so that the needed movements are performed.

In this section we attempt to relate these requirements onto QoS requirements for continuous biosignals delivery. The QoS is widely considered as a performance of data delivery service offered by a network communication path. This performance is measured in terms of QoS characteristics. Since the extra-BAN communication is supported by a wireless link, we examine QoS requirements of continuous biosignals delivery from the perspective of mobile computing area. A comprehensive survey of QoS in the mobile computing environment is presented in [Chal99]. In [Chal99], the QoS characteristics are classified into two groups: *technology based* and *user based*. The user based QoS characteristics describe the quality of data delivery as perceived by the user [Chal99]. Since in the MHPMS, the end-user of delivered biosignals is a healthcare professional, their perception on the quality of data can be described in terms of the following: 1) Are the biosignals needed for decision making are available? 2) Whether the biosignals data being received are of sufficient quality to make a decision? 3) If required, has the patient received feedback well in time to react? However, analyzing the perception of healthcare professionals requires conducting trials of mobile patient monitoring system on the real patients and interacting with the healthcare professionals. These types of experiments which determine the perception of end-users are out of scope of this thesis.

In this thesis, we focus on technology based QoS characteristics for the continuous transmission of the biosignals. These characteristics defined in [Chal99] are *bandwidth*, *timeliness* and *reliability*. The QoS parameters relevant for our work are *goodput*, *round trip time* and *data loss ratio* respectively. The description of these parameters is as follows:

- *Goodput*: The goodput is a useful amount of information delivered per second to the application. The goodput is comparable to the *application level data rate* described in [Chal99]. For the biosignals transmission, goodput refers to the amount of biosignals received per second at the BESys. We name it as the *extra-BAN communication goodput*.
- *Data loss ratio:* The data loss ratio is the proportion of total data that does not arrive as sent [Chal99]. For the biosignals transmission, the data loss ratio refers to the amount of biosignals data per second which can not be sent to the back-end system.
- *Round Trip Time (RTT)*: The round trip time is defined as the time elapsed between sending a request to the destination and receiving the corresponding reply at the source. The RTT is comparable to the *response time* in [Chal99].

For the biosignals delivery, we consider RTT as the time elapsed between the transmission of the message originating from the MBU and receiving corresponding reply.

4.2.1 Related Work on QoS in Telemedicine/E-Health Applications

In recent years, a significant amount of research is reported concerning QoS in telemedicine/E-Health applications. The performance evaluation of a simulated telemedicine network that supports email, web browsing, FTP, voice over IP and video conferencing applications is conducted in [Zamb09]. The QoS parameters considered for these applications are bandwidth, delay and packet loss ratio [Zamb09]. The simulation based performance analysis of joint transmission of voice, video, ECG signals and medical scans data using an UMTS network is presented in [Gáll05]. Similar to [Zamb09], the QoS characteristics considered in [Gáll05] are bandwidth, delay and packet loss ratio [Zamb09]. In [Zamb09], a 3 leads ECG signal is sampled at the rate of 250Hz and requires 12 bits per sample. The bandwidth, delay and packet loss ratio requirements for the transmission of ECG are derived to 1-20 kbps, 1000 milli-seconds and zero, respectively. The research reported in [Zvik09] investigates scenarios for QoS provisioning in the emergency telemedicine using simulations. The QoS parameters considered are bandwidth and delay. In [Zvik09] the bandwidth requirements for the biosignals transmission vary from 80 bits/second to 586 kbps. The MobiHealth project conducted nine trials of the MHPMS in four European countries using 2.5G (GPRS) and 3G (UMTS) wireless communication technologies [Halt04]. These trials used BAN variants to monitor patients suffering from high-risk pregnancy, trauma, cardiology (arrhythmias), rheumatoid arthritis (RA) and respiratory insufficiency (chronic obstructive pulmonary disease). In the MHPMS trials, depending on the biosignals profile, the bandwidth requirements for the transmission of biosignals are from 0.28 kbps to 32.79 kbps [Dima03]. However, for the MHPMS trials, the delay requirements were not explicitly calculated.

Overall, the bandwidth requirements for biosignals delivery are dependent on the sample size of an individual biosignal and corresponding sampling frequency. The values of delay and loss ratio parameters are monitoring application specific. However, since we are not able to estimate the impact of loss ratio on the quality of biosignals received at the back-end, similar to [Zamb09], we consider that the loss ratio of zero. For interactive patient monitoring applications such as remote physiotherapy treatment, RTT is an important parameter, since it is required for a patient to receive feedback from the healthcare professional in time which is based on current state of patient's biosignals received at the terminal of healthcare professional. In the following, we quantify goodput and RTT requirements for three mobile patient monitoring cases presented in Section 4.1.

4.2.2 Estimated Goodput Requirements

The goodput refers to the amount of biosignals received per second at the back-end system. Hence, it does not include extra-BAN communication protocol overhead required to deliver biosignals to the BESys. The goodput requirements combined with extra-BAN communication protocol overhead is equivalent to the bandwidth requirements for biosignals delivery. In the peer research [Widya06], it is assumed that the extra-BAN communication protocol stack overhead per second of aggregated biosignal data is 10% [Widy06]. In this section, we use this assumption to also specify bandwidth requirements for biosignals delivery. However, it is to be noted that the experiments conducted in this thesis are for the goodput requirements.

A description of an irregular ECG pattern detection case presented in [Roch08] states that on the detection of an irregular ECG pattern, the biosignals undergo *Fast Fourier Transform* (FFT) in order to reduce the amount of biosignals to be sent to the application server. The FFT transform results in encoding of all needed information in lesser number bytes than the original representation of an ECG. The ECG signal is obtained from eight ECG leads at the sampling rate of 512Hz. The research reported in [Roch08] does not provide details about the number of bytes required to represent one sample of an ECG signal. Also, the protocol used for extra-BAN communication is not specified in [Roch08]. Hence for calculating estimated goodput requirements, we assume the following:

1) Digital representation of the ECG signal obtained from one ECG lead requires 24 bits [Dima03].
2) A compression ratio of 8 is feasible to achieve using FFT while ensuring clinical acceptability of the resulting ECG signal [Kulk97].

Considering extra-BAN communication protocol overhead of 10%, the goodput requirements and bandwidth requirements for the irregular ECG pattern detection case [Roch08] are shown in Table 4.1.

Table 4.1: Calculation of estimated goodput and bandwidth requirements for the irregular ECG pattern detection case [Roch08]

Sensor Set	*Bit Length*	*sampling frequency*	*Aggregated size*	*compressed size (required goodput in bps)*	*Protocol overhead (10%)*	*Required bandwidth (bps)*
8 leads ECG	8 * 24	512	98304	12288	1229	13517

An example case of remote physiotherapy treatment for a patient's lower back is presented in [Ferg09]. Accordingly, two accelerometer sensors are attached to patient's arms and their position is measured every millisecond. This results in a sampling frequency of 1000Hz. The acceleration values are represented by three parameters which are *accX*, *accY* and *accZ*. The research reported in [Ferg09] does not provide details about number of bytes required to represent one sample of accelerometer signal and the protocol used for extra-BAN communication. Hence for calculating estimated goodput requirements, we assume that the digital representation of the signal obtained from an accelerometer requires 24 bits[15]. Considering extra-BAN communication protocol overhead of 10%, the goodput requirements and bandwidth requirements for the remote physiotherapy case [Ferg09] are shown in Table 4.2.

Table 4.2: Calculation of estimated goodput and bandwidth requirements for the remote physiotherapy case [Ferg09]

Sensor Set	*Bit Length*	*sampling frequency*	*Aggregated size (required goodput in bps)*	*Protocol overhead (10%)*	*Required bandwidth (in bps)*
Accelerometer	2 * 24	1000	48000	4800	52800

Table 4.3: Calculation of estimated goodput and bandwidth requirements for the trauma patient case [Alon02]

Sensor Set	*Bit Length*	*Sampling frequency*	*Aggregated size*	*Compressed size (required goodput in bps)*	*Protocol overhead (10%)*	*Required bandwidth (in bps)*
Respiration	24	64	1536	1536	154	1690
ECG	24	512	12288	3687	369	4056
SPO2	24	128	3072	3072	308	3380
NIBP	8	32	256	256	26	282
Total			17152	8551	857	9408

A description of sensor set, sampling frequency, compression factor and protocol overhead for the trauma patient monitoring case [Alon02] is provided in [Dima03]. While the compression factor for an ECG signal is 0.3, the compression factor is 1 (no compression involved) for the respiration, oxygen saturation and pulse rate sensors. Considering extra-BAN communication protocol overhead of 10%, the goodput requirements and bandwidth requirements for the trauma patient case [Alon02] are shown in Table 4.3.

[15] In practice, there exist many types of accelerometers and the data size is also dependent on the application. The higher is the required precision, the more space is required to represent accelerometer data values.

4.2.3 RTT Requirements

To calculate RTT requirements of continuous biosignals delivery from the MBU to the BESys, we refer to UMTS QoS traffic classification [Lauk00]. The rationale behind this choice is that the UMTS QoS classes take into account restrictions and limitations of the wireless network interfaces [Lauk00]. The UMTS traffic classes are characterized according to delay sensitivity. The UMTS conversational and streaming traffic classes are intended for real-time traffic flows. The conversational class includes applications like video telephony which are characterized by stringent and low delay. The streaming class refers to one way transport such as audio streaming in which the emphasis is on preserving time relation between information entities of the stream. The interactive class contains applications such as web browsing which follow request-response pattern and the emphasis is on preserving payload contents in the request-response messages. The background class is for applications in which destination is not expecting the data within a certain time and the emphasis is on preserving payload content, e.g. background download of emails.

We consider that the remote physiotherapy [Ferg09] and trauma team cases [Alon02] are analogous to the video conferencing service. In both of these cases communication between both the ends (patient and healthcare professional) is necessary. The recommended maximum value of delay for a video telephony application is 150 ms [Ali05, Chen04]. Since the recommended value of one-way delay is 150 ms, the two-way delay is 300 ms. On top of this, we assume that the human response time of a healthcare professional is 200 ms in case the healthcare professional would like a patient to stop doing certain movements which might be harmful for the patient. Combining, we derive a RTT value of 500 ms for the remote physiotherapy and trauma team cases.

We consider that the continuous transmission of the biosignals in the irregular ECG pattern detection case [Roch08] is analogous to an audio streaming service in the Internet [Chen04]. The recommended maximum value of the delay for audio streaming using Internet is 150 milli-seconds respectively [Chen04]. However, in this particular case, it is not required for a patient to receive an immediate response from the healthcare professional. The healthcare professional performs diagnosis using available ECG for which the ECG sample of certain continuous time duration (usually a few seconds) is required. The action taken by a healthcare professional consists of the following: recognition of false alarm, call the patient or dispatch an ambulance to patient's location. Looking at these aspects, we choose not to assume a specific value of one-way delay for the irregular ECG pattern detection case. To our knowledge, further probing in the healthcare domain is necessary for specifying delay value for this type of mobile patient monitoring cases.

4.2.4 MHPMS Experimentation with the Round Trip Time

The MHPMS utilizes *Mobile Service Platform* (MSP) middleware [Halt06] to model biosignals delivery as a nomadic mobile service in the Internet (Section 2.3). In a fixed network, a service consumer uses either an IP address or the server's DNS name to bind to the service provider. However, for the patient monitoring cases, the MBU is a mobile device which is capable of connecting to the Internet using multiple network interfaces. As explained in Section 2.4, while roaming from one network to another, each network may assign different IP address to the MBU causing it unreachable from the surrogate host. Hence, to ensure the reachability of the MBU, MSP proposes a solution of piggybacking messages from the surrogate host to the MBU in a HTTP Response to the HTTP Request originating from the MBU. To enable reception of piggybacked messages from the surrogate host to the MBU, the MBU periodically sends a special type of HTTP request-reply message named as *Keep-Alive message* to the surrogate host (Section 2.4). In this way, the communication problem between the surrogate host and MBU is solved since the TCP connection is alive for receiving HTTP response to the keep-alive message. For this reason, we choose to consider RTT instead of one-way delay for the experiments reported in this thesis. According to the discussion in Section 4.2.3, the value of RTT chosen for experiments conducted in this thesis is 500 ms.

4.3 Vertical Handover Requirements

Based on the state of the art reported in Chapter 3, it is noted that a vertical handover based solution is a proven technique to address wireless network changes resulting from patient mobility. A wide range of wireless networks (LAN, WLAN, GSM, UMTS, WiMAX) are supported by handover management techniques. The handover decision making processes in [Bala09, Ahme06, Wu09, Chen05, and Hong06] take into account QoS requirements of mobile application data traffic for selecting a wireless network. The network availability and QoS information received from *location service server* is utilized in [Chen05] to improve battery life of a mobile device. After presenting this overview, herewith we elaborate on handover information requirements. The handover information presented in this section is grouped into following four categories as per the classification presented in [Kass08]: 1) *Network related information*; 2) *Terminal (MBU) related* information; 3) *User related information*; and 4) *Service (application) related information*. In line with the principles of context-aware computing described in Section 2.5, we refer to the handover information as *context information*. The service related information refers to QoS requirements of continuous biosignals delivery. A description of eliciting QoS requirements for mobile patient monitoring applications is provided in Section 4.2. As illustrated therein, the user related information is out of scope of this thesis. In Section 4.3.1, we present network related handover information requirements. The MBU related handover information requirements are illustrated in Section 4.3.2.

4.3.1 Network Related Handover Information

The MHPMS system uses HTTP protocol for delivering biosignals from the MBU to the BESys. The HTTP protocol in turn uses TCP over IP to send and receive data. In the situations where MBU connects to or disconnects from a wireless network in a dynamic fashion, the knowledge of wireless networks surrounding a MBU is necessary to take a handover decision. In this section, we discuss the following network related handover information, namely *communication context* and *QoS predictions context*.

Communication Context

A MBU communicates with the BESys using various network infrastructure facilities, such as IP address of the wireless network interface, *Domain Name System* (DNS), proxy services or service discovery services. In a multi-homed situation, the MBU has multiple entry points to the DNS, and applications may want to decide or influence, as with path selection, which entry is used to execute DNS lookups [Pedd05]. This information about wireless network can be captured with a stack view and it is named as *communication context* in [Pedd05]. An example of network stack view taken from [Pedd09] is shown in Figure 4.1. In Figure 4.1, the MBU is connected to three access networks namely USB, GPRS and 802.11. Each of the network interfaces of the MBU is assigned an IP address. The established TCP connections are also shown in Figure 4.1.

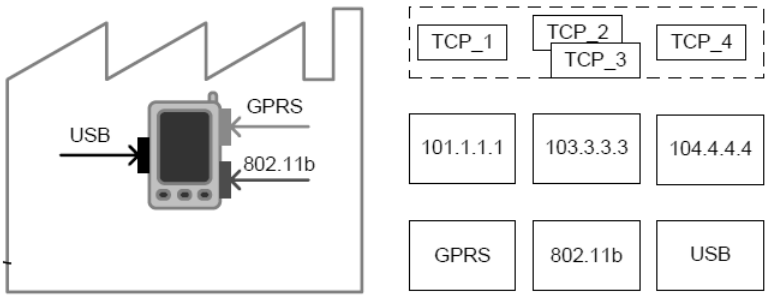

Figure 4.1: The network stack view showing details about MBU connections (adapted from [Pedd09], page no. 26)

Quality of Service Predictions Context

The motivation behind QoS predictions and system architecture for generating these predictions is briefly presented in Section 3.3. The QoS predictions refer to the real-world information that specifies QoS offered by different wireless networks in the vicinity of a mobile device along the following dimensions: *geographical location*, *time*, *wireless access network provider* and *wireless access technology*. An exploratory research reported in [Wac09b] demonstrates that QoS predictions can indeed be derived based on data collected from multiple users. After experimenting with a number of machine learning algorithms, it is concluded that using a J48 *decision tree algorithm* it is feasible to provide accurate predictions of the *keep-alive RTT* by processing historic data collected by that device or other mobile devices. For the description of J48 algorithm and other machine learning algorithms used in QoS predictions experiments, we refer to [Wac09b].

Since the existing work on the QoS predictions generates only RTT predictions and goodput is an important QoS requirement, herewith we propose a hierarchical structure of QoS predictions which include two QoS parameters, namely *goodput* and *RTT*. The first level of this structure consists of basic information which is *validity interval, location range, network type, network name, operator name and authentication* (e.g. `30 minutes, 550 meters, WiFi, Guest WLAN, University of Geneva, and Open`). The validity interval represents a time duration in the future for which the QoS-predictions are valid. After the elapse of validity interval, it is necessary to request new QoS predictions. The location range represents the distance between the farthest network from the current location of mobile device. When a patient moves beyond the location range, it is also necessary to request new QoS predictions. The validity interval and location range together pose a limit on the amount of QoS predictions which are to be sent to the MBU.

It is possible that one network operator has installed multiple wireless networks at multiple locations [Rend07]. E.g., an operator may provide wireless network connectivity at multiple office locations of the same organization. Hence, the second level of QoS predictions is the prediction information in location dimension. This information consists of *geographic coordinates of the centre of the network and radius of the network coverage area* (e.g. `46.179956, 6.13896, 55m`). The QoS characteristics of the wireless networks are location and time dependent [Wac06]. Hence the third level in the prediction information is the QoS values in time dimension which consist of the *predicted goodput, RTT* and *start-time and end-time for which these predicted values are valid* (e.g. `24 APR 2008 13:55:30, 24 APR 2008 14:20:33, 15149 bps, 650 ms`). In the proposed structure, we assume that the wireless network has a circular coverage area. However, this is usually not the case in practice. This issue is addressed further in Section 8.3 on future work.

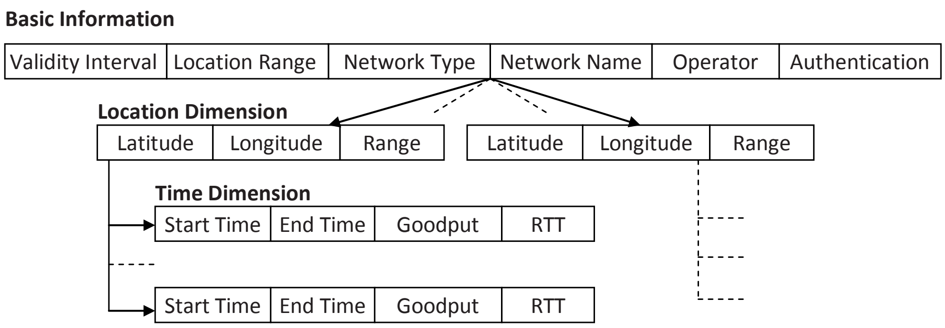

Figure 4.2: Proposed hierarchical structure of QoS predictions

4.3.2 MBU Related Handover Information

The location of the MBU is necessary for offering context-aware functionality such as dispatching healthcare professionals to assist the patient. Hence, *location and time context* is a relevant MBU related handover information. To address the issue of limited battery life of the MBU, it is important to understand the nature of power consumption of the MBU. Hence, the *MBU power consumption context* is also considered as necessary handover information.

Location and Time Context

We represent the location of MBU in terms of geographic coordinates (*longitude* and *latitude*). The time is represented in the format *DAY HH:MM:SS*. Along with the outdoor location detection technologies such as GPS localization [Djuk01], a number of indoor location detection technologies [Liu07] are in use to determine MBU's location in the indoor environment. Hence, it is easy to obtain MBU's location with a fair accuracy e.g. 10 meters or better precision using GPS localization technique [Djuk01]. The mobile devices have in-built clock and in case accuracy problems arise with time, a *network time protocol* (NTP) server can be used for synchronizing clocks. Hence, the location and time information ca be obtained locally on the MBU.

MBU Power Consumption Context

In order to experiment with the power consumption of MBU, the knowledge of power consumption nature of the MBU is necessary. We consider this information as the MBU power consumption context. In line with commercially available handheld mobile devices, we consider that the MBU is equipped with one WWAN network interface (e.g. GPRS and/or UMTS) and one WLAN network interface (e.g. WiFi). From the perspective of data transfer, at any given time, the MBU network interface (NI) can be in one of the following states:

- *OFF*: No IP connectivity.
- *POWERING-ON:* This is an intermediate state to switch on the NI.
- *ON-IDLE*: an *IP-idle* state in which the NI has IP connectivity to the Internet. However it does not send/receive any IP packets carrying application-data.
- *ON-ACTIVE*: an *IP-active* state in which the MBU is sending or receiving application level IP packets through this NI.

Combining the states of WLAN and WWAN NIs, there exist in total 16 different states. The power consumption context includes the *value of power consumption of a particular NI state combination* (measured in *Watt*). The *maximum battery capacity* and the *remaining battery power of the MBU* are also included in the power consumption context and it is measured in *Joules*.

4.3.3 Vertical Handover Mechanism Requirements

Revisiting the survey of vertical handover management approaches and the thesis research problem, we identify following requirements for the vertical handover mechanism to be introduced in the MHPMS.

- Since a patient is mobile and the wireless networks deployment is characterized by uneven geographic distribution, the handover mechanism should be able to detect network availability changes on the occurrence of following events: 1) A patient moves out of the wireless network coverage area; 2) A patient enters the coverage area of a different wireless network.
- Since the wireless network is characterized by variable QoS, the handover mechanism should be able to sense changes in the QoS values and initiate a handover decision making process in case the wireless network currently in use does not meet QoS requirements of continuous biosignals delivery.
- The handover decision making technique should consider both, QoS requirements of biosignals delivery and QoS offered by the wireless network in order to select a network for delivering biosignals.
- At least one of the network interfaces of the MBU must be on to transmit biosignals. However, the possibility of power savings on the MBU by switching off the unused network interfaces while still being able to detect network availability changes should be considered (similar to the approach in [Chen05]).

4.4 Conclusions

In this chapter, we presented three mobile patient monitoring cases in which it is necessary to continuously transmit patient's biosignals from the MBU to the BESys for a certain time duration as determined by the requirements of healthcare professionals. These cases are namely *detection of an irregular ECG pattern* [Roch08], *remote physiptherapy treatment* [Ferg09] and *trauma patient transport* [Alon02]. For the accurate decision making, the healthcare professionals have following requirements on the biosignals being received at the BESys: 1) Certain types of biosignals are must for decision making; 2) The quality of biosignals being received should be good enough so that the decision making is not affected; 3) In case the decision taken expects the patient to take a certain action, then the feedback should be received by the patient in time to react. Since the biosignals are transmitted using wireless network connectivity, we map these requirements onto QoS requirements of biosignals delivery. The QoS parameters relevant for our work are *goodput*, *data loss ratio* and *round trip time* respectively.

We derived biosignals goodput requirements by multiplying sample size of an individual biosignal to corresponding sampling frequency of that biosignal. In addition, compression factor if any is also to be considered. The relationship between goodput requirements and bandwidth requirements is determined using transmission protocol overhead. Similar to [Zamb09] we consider the packet loss ratio of zero. To determine RTT requirements of a mobile patient monitoring application, we consider that the remote physiotherapy case [Ferg09] and trauma team case [Alon02] are analogous to the video conferencing service. Based on related literature [Lauk00, Ali05, Chen04] and to allow a patient to receive feedback on time, we came up with the RTT value of 500 ms for both of the mobile patient monitoring cases in [Ferg09, Alon02]. The irregular ECG pattern detection case presented in [Roch08] is analogous to the streaming service. In this case, the strict values of RTT and delay parameters cannot be calculated, as the biosignals of certain duration are required to assess patient's medical condition. Further research in the healthcare domain is necessary for specifying delay value for the type of mobile patient monitoring cases presented in [Roch08]. The resulting QoS requirements for each of these cases are shown in Table 4.4.

Table 4.4: Derived QoS requirements for the continuous transmission of biosignals

Example case	***Goodput (bps)***	***Bandwidth (bps)***	***RTT***	***One-Way Delay***	***Data loss ratio***
Detection of irregular ECG pattern [Roch08]	12288	13517	Not applicable	Unknown	0
Remote physiotherapy treatment [Ferg09]	48000	52800	< 500 ms	<150 ms	0
Trauma patient [Alon02]	8551	9408	< 500 ms	<150 ms	0

The handover related information for addressing thesis research problem is grouped into three categories: *service related information* (QoS requirements for the biosignals transfer), *network related information* (communication context and QoS predictions context) and *MBU related information* (location and time context, MBU power consumption context). The context information and motivation behind its selection is presented in Table 4.5.

Table 4.5: Handover information requirements

Information type	***Context Information***
QoS requirements context	Biosignals delivery QoS requirements (goodput and RTT based on the signal profile of the monitoring service
Communication context	A list of wireless networks along with provider names, technologies, maximum uplink bandwidth and delay in the surroundings of a mobile device (details in [Pedd05, Pedd07]).
QoS-Predictions Context	All available wireless networks as specified by provider names, network names and technologies along with their coverage ranges and availability at a given location/time and predicted QoS

	information (goodput and RTT). (details in [Wac06, Wac08, Wac09b])
Location and Time context	Coordinates of the device's current geographic location (longitude, latitude) and time (Date, HH:MM:SS).
MBU Power consumption context	Maximum battery capacity and current power level of the battery of MBU, available network interfaces, power consumption in Watt by a combination of network interface states.

Chapter 5

Mobile Controlled Vertical Handover Mechanism[16]

Research objective 2 of this thesis is the following: How to use a vertical handover technique to maintain HTTP connectivity to the MBU in the events of patient mobility and network outage? In this chapter we propose a context-aware *Mobile Controlled vertical HandOver* (MCHO) mechanism to address this research objective. Research objective 5 of this thesis is the following: What are the gains achieved by proposed vertical handover mechanisms and what are the corresponding overheads? In this chapter, we report conducted experiments and obtained results to address this research objective.

This chapter is organized as follows: Section 5.1 re-introduces the problem briefly and motivates a choice of context-aware computing based architecture. Section 5.2 presents architecture and implementation of proposed MCHO mechanism and provides justification about component choices. Section 5.3 lists performance evaluation objectives for evaluating proposed mechanism. Section 5.4 outlines experimental setup for validating proposed mechanism. Section 5.5 discusses obtained results and findings. Section 5.6 presents conclusions.

5.1 Introduction

The MHPMS components described in [Halt04] are the following: *sensor system*, *Mobile Base Unit (MBU)*, *back-end server* and *vital signs display terminal* located at the health-care professional's site. The sensor system and the MBU together comprise a *Body Area Network* or so called BAN, and the communication between them is referred as *intra-BAN communication*. The BAN and the back-end server communicate with each other using HTTP messages and this communication is referred as *extra-BAN*

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[16] A part of this chapter is based on our work published in [Pawa07b, Pawa07c, [Pawa08b and Wac09c].

communication. It requires availability of Internet connectivity to the MBU which is provided by *wireless Internet service providers* (ISPs). As described in Chapter 4, depending on the mobile patient monitoring application case, the delivery of biosignals to the healthcare center has associated goodput, RTT and data loss ratio requirements, which together form the *QoS requirements of biosignals delivery*. The *extra-BAN communication path* i.e. the biosignals delivery path from the MBU to the back-end server consists of multiple heterogeneous networks, among which the first hop is a wireless network to which MBU is connected. This view of the MHPMS is shown in Figure 5.1.

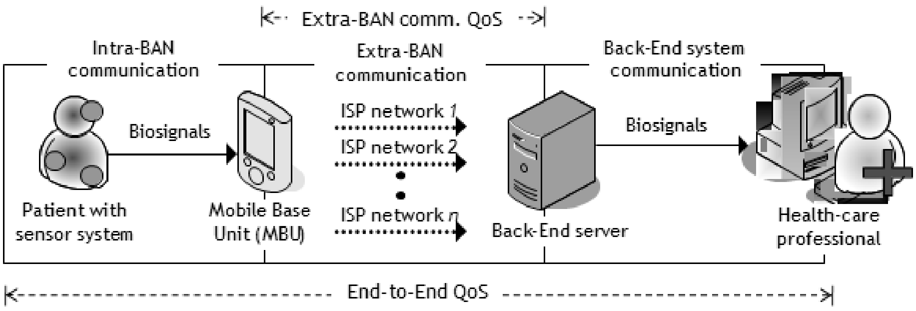

Figure 5.1: Abstract QoS view of the MobiHealth patient monitoring system

5.1.1 Problem

The mobility of a patient combined with an uneven geographic availability of wireless networks results in changes in the availability of wireless networks surrounding the MBU. This affects continuity of patient monitoring. The real-life trials of MHPMS [Halt04, Alon02] have shown the feasibility of using MHPMS system, however a number of problems are reported. The problems related to the use of wireless networks are the following: In the area of wireless networks (including GPRS and UMTS) the patient monitoring suffers from limited bandwidth, specially for the monitoring applications those require monitoring many simultaneous biosignals per user. In the situations where a patient moves from an area of higher bandwidth to an area of lower bandwidth eventually a situation occurs where the wireless connection is lost [Halt04]. A similar behavior is observed during the trial of other mobile patient monitoring systems (Chapter 3). The following statement is repeated from the conclusions on the study of mobile patient monitoring systems: The wireless network problems refer to the lack of sufficient bandwidth for the transmission of signals, high delay and unavailability of the wireless network coverage. To solve these problems, in this chapter, we propose use of vertical handover in the mobile patient monitoring systems.

5.1.2 Vertical Handover and the Use of MBU Network Interfaces

The process of vertical handover and its benefits for solving user mobility problems and wireless network connectivity problems are explained in Section 3.2. Based on the literature survey, it is observed that a vertical handover based solution is necessary to address research objective 2. In such solution, it is expected that the MBU performs user-unobtrusive handover to the wireless network of choice and uses selected wireless network for delivering biosignals to the BESys. In case the MBU is multi-homed, it can be argued that all network interfaces (NI) of the MBU can be used simultaneously for transmitting biosignals. However, in the MHPMS implementation, it is possible to specify only one IP address to use on the MBU to send biosignals packets to the BESys. This requires that the vertical handover based patient monitoring system selects and uses one NI at a time for delivering biosginals and other data (e.g. control messages such as keep-alive mess) to the BESys. Hence the solution of using multiple NIs simultaneously for biosignals delivery is not considered.

5.1.3 Motivating Use of Context-Aware Computing Based Architecture

The choice of context-aware computing based architecture is motivated based on a survey paper titled *Using Service Oriented Computing in the Development of Context-Aware Systems: Domain-Model Approach* [Wac09c]. The *context-aware computing paradigm* [Schi94] is closely related to other user-centric computing paradigms (e.g. ubiquitous computing, pervasive computing, ambient intelligence, location-based computing, calm computing, intelligent or smart computing, and emotional computing). All of these computing visions have in common strive for the goal of delivering personalized applications and services to users by employing mobile and embedded devices which are integrated seamlessly in the user's everyday environment. One may argue that context-awareness has a more restricted scope than these research paradigms. However, as this paper demonstrates, context awareness is an extensively researched area and has far reaching applicability. According to us, context awareness plays an important role in paving the way for these paradigms in realizing personalized applications (Figure 5.2). Context-aware computing paradigm provides a framework illustrating guidelines for the development of systematic information processing channel, which receives an input from the software and hardware sensors and produces an output of which can be used to achieve adaptive behavior aimed by above paradigms (we refer to the layered model of context-aware computing systems presented in Section 2.5.3).

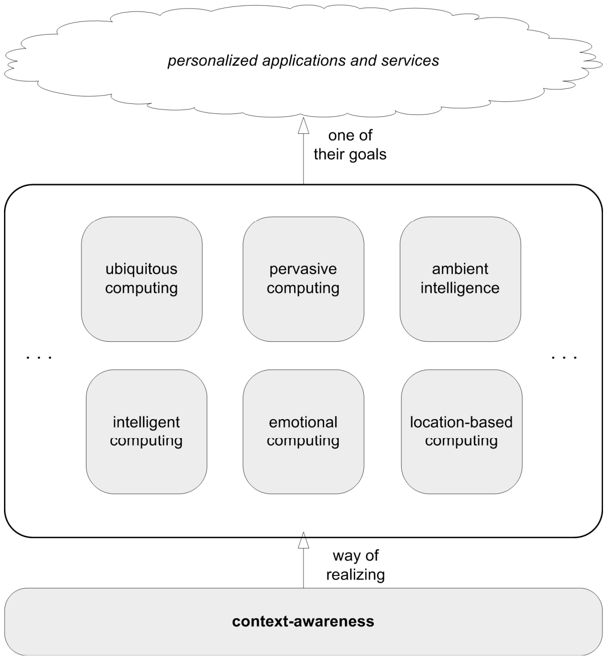

Figure 5.2: Relationship between context-aware computing paradigm and other user-centric computing paradigms [Wac09c]

In the overview of vertical handover decision strategies presented in [Kass08], it is noted that a context-aware computing based vertical handover strategy is highly efficient, highly flexible and supports both, real-time and non-real-time services. Context-aware computing based vertical handover mechanisms are used in [Bala04, Ahme06] for handheld mobile devices and they are validated for use on these devices (as opposed to simulation based validation). Given this discussion, we also employ context-aware computing based architecture for the proposed solutions.

As illustrated in Chapter 3, a handover management process is composed of following three phases [Kass08]: 1) *Handover information gathering* phase collects information required to identify need for a handover and initiate the handover; 2) *Handover decision making (network selection)* phase determines a network suitable for handover execution; and 3) *Handover execution* phase performs actual handover to a network selected by the second phase. In the implementation of both of these approaches, context sources and context processor contribute to a handover information gathering phase. A context reasoner takes care of a handover decision making phase. Finally, a phase of handover execution is supported by *stream worker* and *message worker* components of the MSP middleware.

5.1.4 Why Two Vertical Handover Mechanisms?

In this thesis, we proposed two context-aware vertical handover mechanisms for use in the MHPMS. The first mechanism is mobile controlled handover mechanism (MCHO mechanism reported in this chapter) and the second mechanism is network assisted handover mechanism (NAHO mechanism reported in Chapter 6). The reason behind proposing two vertical handover mechanisms is mainly due to availability of context sources providing information necessary to take a vertical handover decision. The context-aware computing paradigm provides flexibility of using one or more context sources depending on their availability. The handover information required to address the thesis research problem is presented in Section 4.3. The identified context information is: *QoS requirements context, communication context, QoS predictions context, location & time context and MBU power consumption context*.

During the design of MCHO mechanism, the communication context source was readily available in the form of COSPHERE [Pedd05] as well as it is also implemented and tested on the type of mobile devices used as MBU in the MHPMS. The COSPHERE communication context source is also a part of PhD research in the AWARENESS project [Pedd09]. The MCHO mechanism uses COSPHERE for obtaining communication context information and its use in the MHPMS is firstly reported in [Pawa07c].

In the later stages of research work, we hypothesized that the use of QoS predictions will prove more beneficial for use in the MHPMS. A sound concept of QoS predictions firstly appears in [Wac06]. The data necessary to generate QoS predictions is obtained from mobile devices which use MHPMS patient monitoring application for sending passive QoS measurement data to the QoS predictions engine [Section 3.3]. The NAHO mechanism reported in Chapter 6 uses QoS predictions and it is firstly reported in [Pawa08c]. For the motivation, architecture, experimentation and evaluation of QoS predictions, we refer to [Wac09b].

5.2 The Architecture of Mobile Controlled Handover Mechanism

The vertical handover mechanism proposed in this chapter aimed at ensuring HTTP connectivity to the MBU in the events of patient mobility and network outage. In order to do so, the handover mechanism should be able to detect network availability changes on the occurrence of following events: 1) A patient moves out of the wireless network coverage area; 2) A patient enters the coverage area of a different wireless network; and 3) The wireless network suddenly becomes unavailable. In order to solve this problem using context-aware computing based architecture, a context source is necessary that can provide information about these events for handover decision making. In the proposed architecture, we choose a context source named COSPHERE [Pedd07] that provides information about wireless networks surrounding the MBU. The context processor component is introduced in MHPMS to process context information obtained from the COSPHERE. The context reasoner component is introduced in MHPMS to take a network selection decision. The COSPHERE component is designed to run on the MBU. The architecture of MHPMS supporting MCHO mechanism is presented in an abstract form in Figure 5.3. All the elements shown in Figure 5.3 including context sources, context processor and context reasoner are hosted on the MBU. Since the MBU executes and controls the handover management process, the proposed mechanism is referred as *Mobile-Controlled HandOver* (MCHO) mechanism. Compared to the MHPMS architecture described in Section 2.6, the elements shown in a dotted rectangle are introduced newly by the work reported in this chapter. The interactions between various components are shown as a sequence diagram in Figure 5.4.

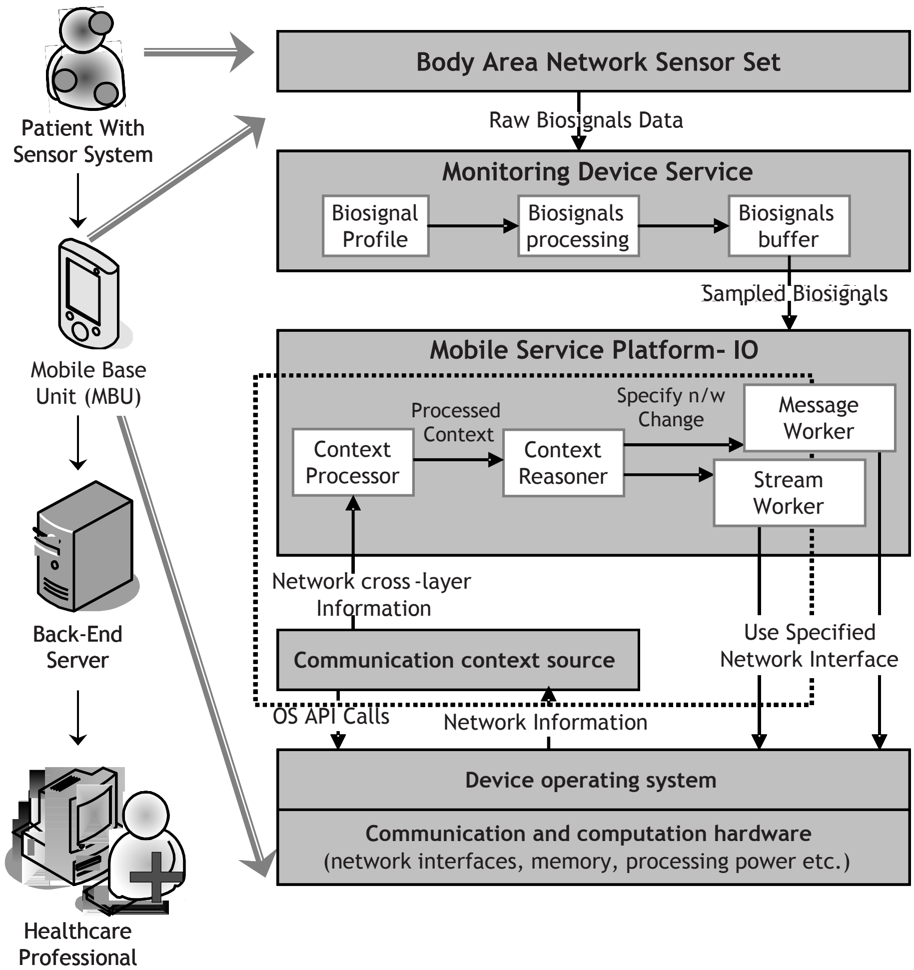

Figure 5.3: Elements of the mobile controlled handover mechanism

5.2.1 New Components Introduced in the MHPMS

- *Communication context source (CCS)*: Most modern operating systems for high-end handhelds provide means to observe and control the state of MBU network interfaces. Additionally, the operating system through the standardized *Socket API* may inform applications on the state of *IP settings* associated with currently active networks. The *communication context source* (CCS) named COSPHERE uses this theory to to obtain information about the wireless networks surrounding the MBU. THe COSPHRE is intended to provide applications running on a mobile device with the following HTTP connectivity related information: the type of wireless network(s) to which MBU is connected (e.g. WLAN, GPRS), IP address of the MBU network interface(s) and whether the network(s) provides HTTP connectivity. An instance of network stack view showing details about MBU connections is shown in Figure 4.1. The network stack information is structured according to the *Network Resource Model* introduced in [Pedd07]. The network resource model defines a relationship between available entities at the *link*, *network* and *transport* layers. The CCS describes a network resource model using XML. The CCS offers a subscription mechanism to send messages about changes in the communication context.

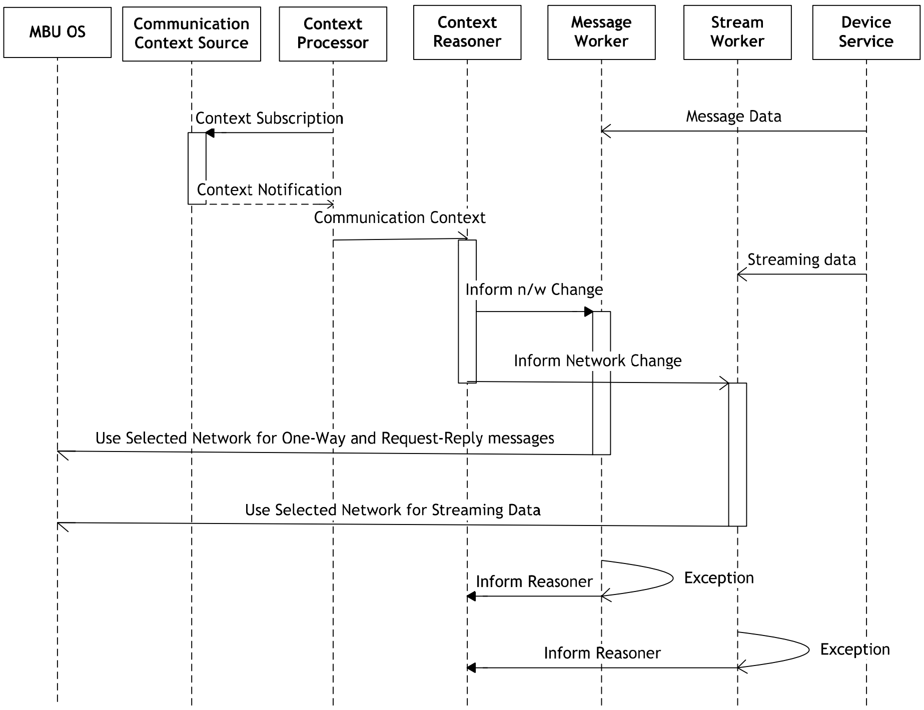

Figure 5.4: Sequence diagram showing interactions within the elements of MCHO mechanism

- *Context processor:* Once a monitoring device service is activated, the context processor obtains initial network stack view from the CCS and subscribes to it for the *context change events*. A context change event is triggered when the MBU joins a new network or disconnects from one of the connected networks. It is to be noted that CCS does not maintain any network information, instead just notifies network change events. In contrast, the context processor maintains a complete network stack view. After receiving each context change event, context processor updates the current network state and sends this information to the context reasoner.
- *Context Reasoner*: The context reasoner uses network state information obtained from the context processor, and associated *link capacity* to take a decision on which network access link (and thus which device interface) to use for communication with the back-end server. The wireless network selection criterion used in context reasoner considers the parameters *maximum bandwidth capacity* and *availability* of the wireless network. E.g., in case the MBU is connected to WLAN and GPRS networks, WLAN will be preferred over GPRS as it has higher maximum bandwidth capacity than the GPRS network. The choice of using these parameters for handover decision making is limited due to use of only one context source in the MCHO mechanism. However, the handover decision making algorithm of the NAHO mechanism proposed in Chapter 6 has a more sophisticated wireless network selection criterion. Moreover, we did not consider use of link layer parameters such as *Received Signal Strength* (RSS), Carrier-to-Interferences Ratio (CIR), *Signal-to-Interferences Ratio* (SIR) and *Bit Error Rate* (BER) in the selection of wireless network as there is no fixed relationship between the application level bandwidth available to the mobile application and value of these parameters. If the wireless network selected by a context reasoner is different than the one currently in use, the context reasoner informs the message worker and the stream worker about the availability of new network connectivity. In case of unavailability of any wireless network, the device service is notified of the unavailability of Internet connectivity.

5.2.2 Implementation of the MCHO mechanism

The design of MSP is based on *Jini technology* [Wald99]. The communication between the monitoring device service and monitoring surrogate is based on Jini *surrogate architecture specification* [Jini01] (Section 2.3.3). A monitoring surrogate participates in the Jini federation. The MSP consists of an HTTP implementation (referred to as *HTTPInterconnect*) of the *Interconnect* protocol in [Jini01] so that the device service is able to communicate with its surrogate. The device service is usually implemented using J2ME technology. The details of MSP implementation are illustrated in Section 2.4.

The CCS implementation is based on the *Network Abstraction Layer* (NAL) reference implementation for *Windows CE* [Pedd07]. It generates network resource descriptions in XML. The NAL implementation consists of almost 11000 lines of C code (.c and .h files) and has an executable size (.exe and .dll-s) of 90kB. The *802.11 plug-in* gathers information about available WLAN networks and associating access points. By default, it obtains a list of access points every 5 seconds. Similarly, the *cellular network plug-in* retrieves information on in-range GSM/GPRS networks and operators. As most of the other components in MHPMS are implemented in Java, and NAL is a native code, a client DLL was developed to interface NAL with the *Java Virtual Machine*. The client DLL maintains a full-duplex pipe to the NAL implementation in order to send XML data back and forth.

The context processor, context reasoner, message worker and stream worker are parts of the MSP-IO package. The context processor is a thread which interfaces with the CCS using the principles of *Java Native Interface* (JNI). The client DLL has an executable size of 8 kB. The context processor and context reasoner have together an executable size of 14 kB. The context reasoner uses KXML library [Robe03] to parse XML representation of the network state. The KXML library has an executable size of 37 kB. The message worker and stream worker are also threads and use *Apache HTTPClient library* to send messages and transmit streaming data to the surrogate host. The context reasoner converts the IP address of a new network interface to the *InetAddress* and changes the *hostConfiguration* property which is later used by the *HTTPClient* to open an HTTP connection. In case of unavailability of the Internet connection, the monitoring device service is notified by means of a Java exception.

5.3 Performance Evaluation Objectives

The MCHO mechanism is aimed at maintaining Internet connectivity to the MBU in the events of patient mobility and network outage using a vertical handover technique. In addition, the wireless network selection criterion selects a wireless network with the highest bandwidth capacity among available wireless networks. Hence, to measure gains achieved by the MCHO mechanism, we propose parameters for measuring *network performance* (Section 5.3.1). To measure the performance of vertical handover functionality, we propose parameters for measuring *vertical handover performance* (Section 5.3.2). Since the MCHO mechanism is implemented on the MBU, we are also interested to measure resources usage on the MBU.

5.3.1 Network Performance

Since the biosignals delivery has associated QoS requirements in terms of the required goodput and RTT, the performance of wireless network to which the MBU is connected is measured using the following parameters:

- *Biosignals Delivery Goodput:* This is the average amount of biosignals data correctly received at the surrogate host per second for a given biosignals profile during a mobile patient monitoring session.
- *Keep-alive RTT:* The RTT of selected wireless network is represented by the parameter *Keep-alive RTT* parameter of MSP.
- *Monitoring Service Buffer Fill Level:* Since the monitoring service buffer fill level is an indicator of the number of biosignal data packets awaiting their transmission, it is also one of the indicators of goodput. The lower the buffer fill level, the higher is goodput. Hence, we observe the dynamics of service buffer-fill level during the experimentation.

5.3.2 Vertical Handover Performance

There is a certain latency involved between the time when handover is needed and the time at which handover is executed. Handover latency is a sum of delays involved in the following three phases of vertical handover: *handover detection*, *handover triggering* and *handover execution* respectively [Bern04]. The delay involved in the individual phases is measured as per the following [Bern04]:

- *Delay of detecting lower layer events*: This is the delay between the occurrence of a particular event (E.g. wireless network connectivity/disconnectivity) in the system and a notification reporting that event. In our case, CCS detects events such as availability of a new network and informs the context processor component.
- *Delay for configuring a new IP address (D_t)*: This delay is defined as the time elapsed between the reception of network change event from the CCS and instructing message worker and stream worker components of MSP-IO to use the new network interface. This delay involves creating current state information at the context processor, selection of the network by the context reasoner, converting an IP address of new network interface to the *InetAddress* and changing the *hostConfiguration* property which is later used by the *HTTPClient* in the stream worker and message worker components to open a HTTP connection.
- *Handover execution delay (D_e)*: This is the delay incurred after configuring a new IP address till the arrival of biosignal packets at the surrogate.

However, we did not focus on the delay for detecting the lower layer events because CCS is developed by a third party [Pedd07]. We are interested to measure D_t and D_e to know the vertical handover latency at MSP-IO. To determine value of D_t, we record timestamps of *CCS network change event*, *wireless network selection event*, *IP address conversion event* and *changing hostConfiguration property event* on the MBU. To determine value of D_e, we record the timestamp at which first biosignals data packet arrives at the surrogate host after vertical handover. For every new experiment run, we reset the MBU as well as the BESys. If necessary, the clocks of MBU and BESys are synchronized using a *network time protocol* (NTP) server.

5.3.3 Resource Utilization on the Mobile Device

Though today's handheld mobile devices have enhanced capabilities, these devices still have limited resources compared to the desktop and notebook computers. Because of the number of buffers in the remote patient monitoring system, a considerable amount of memory is used on the MBU. The operations such as filtering and aggregation of biosignals obtained from the BAN sensor set involves certain processing, which may be demanding for the mobile device [Mei07]. Because of these factors, we are also interested to monitor the processor utilization and memory usage of the MBU during the performance evaluation. Another resource on the MBU is MBU battery power. A detailed study of MHPMS analyzing power usage of MBU during biosignals transfer is reported in [Wac09a]. We use the results of this study further in Chapter 7 while analyzing power savings aspects of NAHO mechanism proposed in this thesis.

5.4 Experimental Setup for the Performance Evaluation

The proposed MCHO mechanism is validated and its performance is evaluated using an experimental setup. This section describes the system under test of this setup and provides an overview of measurement data collection points.

5.4.1 System under Test

The system under test used for performance measurement of MCHO mechanism is shown in Figure 5.5. In this system under test, the MBU used is a QTEK *9090 pocket PC* running the *Windows Mobile 2003 Second Edition* operating system with the *Intel PXA263 400 MHz processor*, *128 MB RAM* and *32 MB* flash memory. It is equipped with a GPRS interface, a WLAN (Wi-Fi) interface and a USB interface. The GPRS connectivity is provided by *Vodafone NL*. The maximum uplink bandwidth provided by the GPRS network is *26 kbps* (using 2 time slots). Our test-bed uses IEEE 802.11b for the WLAN. A BAN consists of a MBU and a sensor set. The MBU communicates with the BAN sensor set using Bluetooth connectivity. A surrogate host runs on a server connected to the University of Twente's fixed network. The tool to log memory and CPU percentage on the QTEK 9090 Pocket PC is a variant of the *Task Manager 2.7 tool* [Cler06]. It is to be noted that there is no involvement of patients in these experiments. The experiments are conducted in office premises.

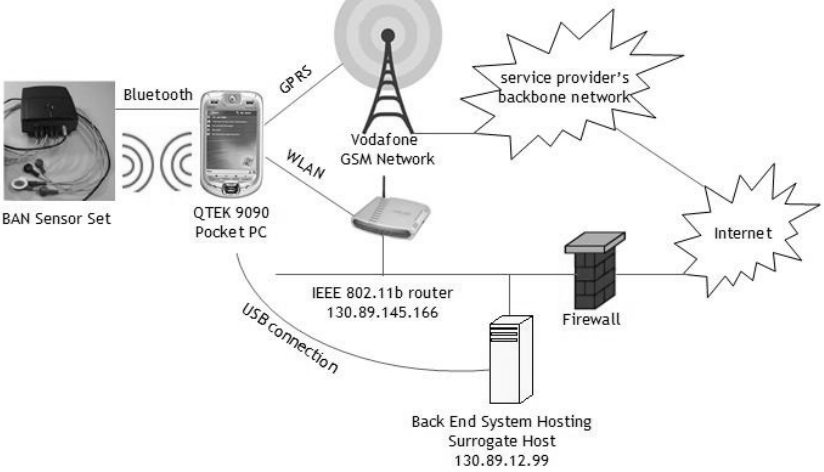

Figure 5.5: Test-bed setup for the performance evaluation of MCHO mechanism

QoS Requirements for conducted experiments

The MHPMS has focused on developing a generic BAN which can be used for a particular type of treatment by using specific set of sensors and implementing appropriate application functionality. E.g., a BAN may have different sensors for patients suffering from high-risk pregnancy, trauma, and cardio-vascular diseases. In the MHPMS, the *biosignals profile* consists of particulars about the biosignals to be sent to the health-care professionals. These include name of the channel associated with a particular biosignal, sampling frequency of a biosignal and length in bytes of the biosignal data. This profile varies in accordance with the biosignals to be collected. The biosignals profile is used by the MHPMS monitoring device service to obtain the biosignals of patients and deliver them to the back-end system. There are a number of biosignals profiles designed in the HealthService 24 project [eTen05]. For the experiments conducted herein, we use two biosignals profiles, namely *cardio biosignals profile* and *generic monitoring biosignals profile*. The purpose of choosing more than one biosignals profile for the experiments is to be able to analyze proposed handover mechanism for a multiple set of QoS requirements. According to the discussion in Section 4.2.4, the RTT requirement for both of these biosignals profiles is set to 500 milli-seconds. These biosignals profiles are described herein.

The cardio biosignals profile: The description of biosignals in the cardio biosignals profile is presented in Table 5.1. Accordingly, the biosignals delivery goodput requirement of cardio biosignals profile is calculated to 25880 bytes.

Table 5.1: Description of biosignals in the cardio biosignals profile

Sensor	***Bit Length***	***sampling freq (Hz)***	***Aggregated size (goodput requirement in bps)***
ECG1	24	256	6144
ECG2	24	256	6144
ECG3	24	256	6144
Resp	24	32	768
SaO2	8	1	8
Pleth	8	64	512
PulseRate	8	2	16
SensorStatus	8	256	2048
Digi	8	256	2048
SawTooth	8	256	2048
Total			***25880***

The *generic monitoring biosignals profile*: The description of biosignals in the generic monitoring biosignals profile is presented in Table 5.2. Accordingly, the biosignals delivery goodput requirement of cardio biosignals profile is calculated to 36864 bytes.

Table 5.2: Description of biosignals in the generic monitoring signal profile

Sensor	***Bit Length***	***sampling freq (Hz)***	***Aggregated Size (goodput requirement in bps)***
ECG1	24	256	6144
ECG2	24	256	6144
ECG3	24	256	6144
Aux	24	256	6144
SaO2	8	256	2048
Pleth	8	256	2048
PulseRate	8	256	2048
SensorStatus	8	256	2048
Digi	8	256	2048
SawTooth	8	256	2048
Total			***36864***

5.4.2 Data Collection Points

Considering the performance evaluation parameters illustrated in Section 5.3, we instrumented nine data collection points. Based on data collected from these data collection points, values of the performance parameters are computed off-line. The collection points are shown in Figure 5.6. The data collected at each point are:

1) Number of bytes of biosignals data being written to the monitoring service buffer;
2) Monitoring service buffer fill level percentage;
3) Number of bytes of biosignals being sent by the message worker and stream worker to the MSP-IO;
4) Number of bytes of the biosignals and control messages being sent over the selected communication network;
5) Delay D_t for configuring a new IP address;
6) Memory and CPU utilization;
7) Handover execution delay D_e;
8) Number of bytes of biosignals and control messages received;
9) Round-Trip-Time of the Keep-Alive messages.

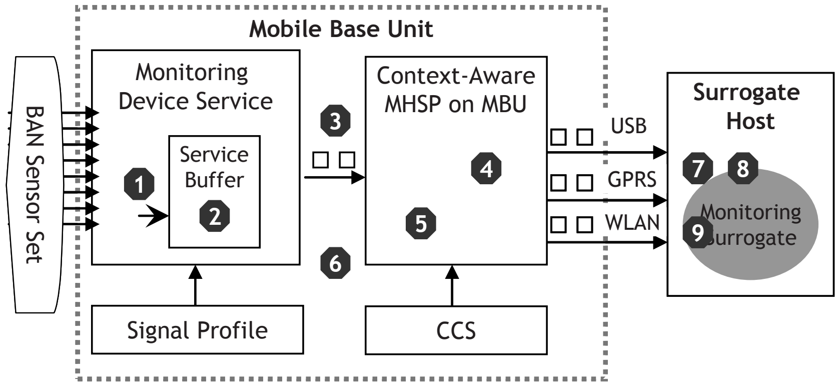

Figure 5.6: Overview of data collection points

Regarding the time span in which we conducted our experiments, we have taken care of the following potential problem. From the test bed setup shown in Figure 5.5, it follows that the WLAN access point is dedicated to the MBU, whereas the GPRS network used is operated by a public network operator. We choose to use dedicated WLAN access point for experiments to be able to create a condition for forced handover by manually unplugging WLAN base-station from the power outlet. In particular, we deployed the WLAN access network without background traffic. The GPRS access network will in general have background traffic, of which we have no quantitative knowledge. Therefore, there is a potential problem that under the circumstances in which the measurements are performed; the measurement results are incomparable. However, these measurements are carried out at the University of Twente at late-night times. This has two main factors. Firstly, the university is located outside of the dense city area. Secondly, at night-times GPRS traffic is expected to be low. The combination of these two makes the likelihood high that the background traffic in the GPRS access network is minimal. We therefore conclude that under these circumstances a fair comparison of results can be made.

5.5 Experiment Runs, Results and their Interpretation

In this section, we provide a description of experiment runs, present obtained performance evaluation results and interpret them. The experiment runs are of three types: *network performance experiments, vertical handover experiments* and *resources utilization experiments*. The results provided in this section are divided into following three categories: *Network performance results*, *vertical handover performance results* and *system resources utilization results*.

5.5.1 Experiment Runs

Network Performance Experiments

With the three interfaces of a MBU, and two different handover scenarios (user handover and forced handover) we have conducted a number of experiment runs for both of the biosignals profiles. For the network performance results reported in Section 5.5.2, the following is a sequence of actions for the Cardio profile:

1) The MBU is connected to the GPRS network all the time.
2) The MBU is connected to WLAN, which results in a handover to the WLAN network.
3) After some time, we switch off the WLAN base-station, which results in the forced handover to the GPRS network.
4) While connected to the GPRS network, when the monitoring service buffer fill level reaches its maximum value (because both the cardio and generic monitoring profile generate data at a higher rate than can be transferred over the GPRS interface), we connect MBU to the USB interface. After this step, MBU uses USB connectivity.

For the generic monitoring profile, in addition to above steps, two handovers, one from the GPRS to WLAN network and other from the WLAN to GPRS network have been performed.

To study the suitability of a network used for biosignals delivery, we run the monitoring service for the duration of 30 minutes and observe steady state biosignals data transfer goodput and Keep-Alive RTT over the selected network. There are no handovers involved during this type of measurement. The results of measured *Buffer Fill Level*, *Keep-Alive RTT* and *biosignals delivery goodput* are described in Section 5.5.2.

Vertical Handover Experiments

Similar to [Bern04] we study the system behavior and performance for the following two different handover scenarios:

1. *User handover (triggered manually)*: A WLAN interface in use is disabled/enabled using WLAN connection settings on the MBU. For the USB interface, we insert/remove the MBU in the USB cradle.
2. *Forced handover (using unplugged base-station)*: A WLAN base-station is disabled by unplugging it from the power outlet. The unplugging of WLAN baste-station models the condition of a sudden network outage.

The forced handover can be performed only for handover to the WLAN network. This is because it is possible to manually power off the WLAN base-station, thus forcing the MBU to use other available network. Since it is not possible to switch off the GPRS base-station, results reported for the forced handover in Section 5.5.3 do not include handovers between the USB and GPRS networks. The handover experiment is repeated for about 10 times for each possible handover in-between the GPRS, WLAN and USB networks.

MBU Resources Usage Experiments

To obtain the resource utilization of the MBU, the log of memory and CPU utilization of the MBU is recorded during one of the experiment sessions.

5.5.2 Network Performance Results

The graphs in Figure 5.7 and Figure 5.9 show the *monitoring service buffer fill level measured at the mobile device vs. time* for the cardio and generic monitoring signal profiles respectively. The graphs in Figure 5.8 and Figure 5.10 show the *amount of biosignals data received at the surrogate (in Bps) vs. time* for these profiles respectively. Since the graphs are colored, in these graphs, the dotted lines are additionally shown for the convenience of reader where colored copies of graphs are not available.

In Figure 5.7, for the Cardio signal profile, while the GPRS interface is in use, the buffer fill level increases gradually. On connecting later to the WLAN, this level drops rapidly because of higher throughput (8678 Bps) provided by the WLAN network. This throughput peak in Figure 5.8 at time *00:11:31* coincides with emptying the buffer as seen from Figure 5.7. After the WLAN base-station is switched off, it takes certain amount of time to connect to the GPRS network. This is the time required to obtain an IP address from the GPRS network. We observed that this duration varies from time to time. Similar to the transition from GPRS to WLAN, a transition from GPRS to fixed network (USB connection) also results in emptying the buffer, as seen in Figure 5.7. Figure 5.8 shows that when the MBU is connected to the fixed network there is also a data throughput peak (16256 Bps). For the generic monitoring profile, we observe similar behavior for the service buffer fill level (Figure 5.9) and the biosignals data transfer goodput (Figure 5.10). The highest goodput provided by the WLAN network is 10396 Bps.

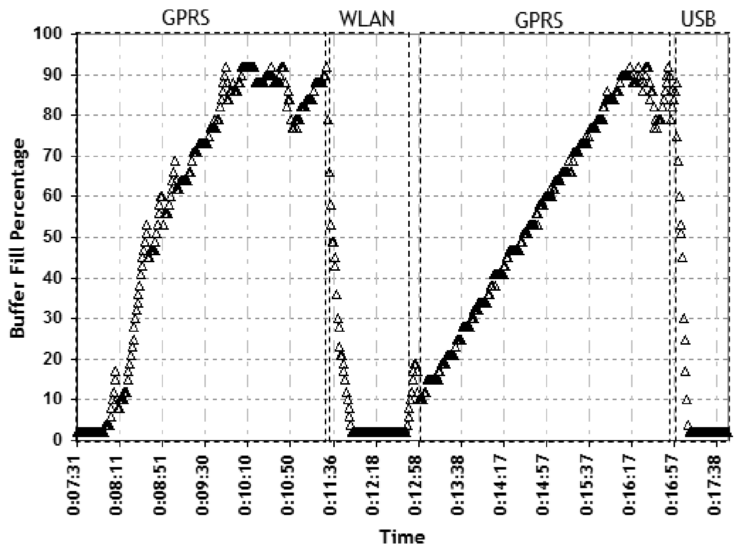

Figure 5.7: Monitoring device service buffer fill percentage vs. time for the cardio profile (as measured on the MBU)

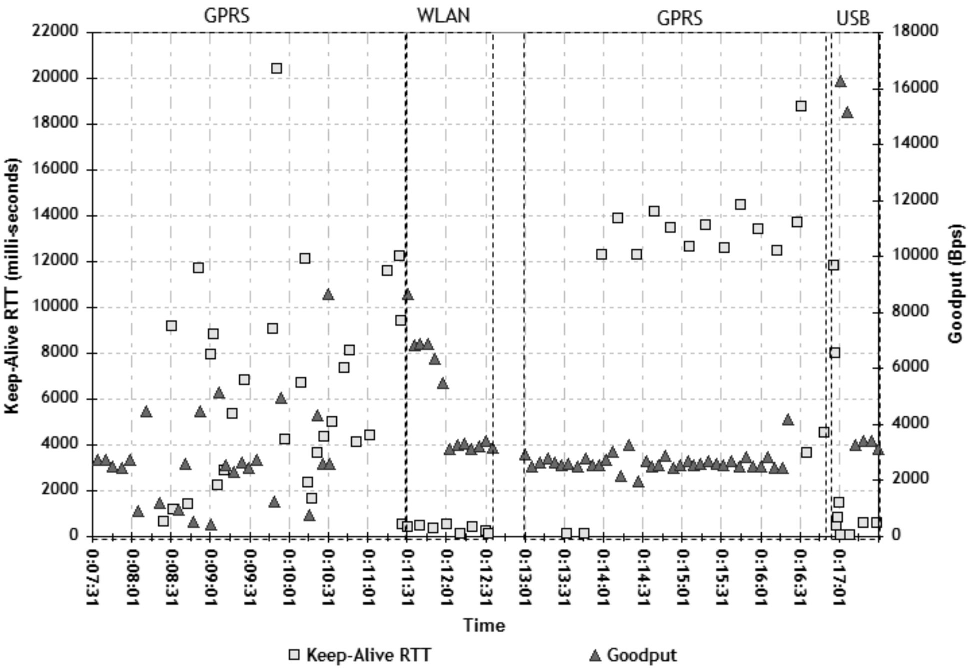

Figure 5.8: Biosignals data transfer goodput and Keep-Alive RTT vs. time for the cardio profile (as measured on the surrogate host)

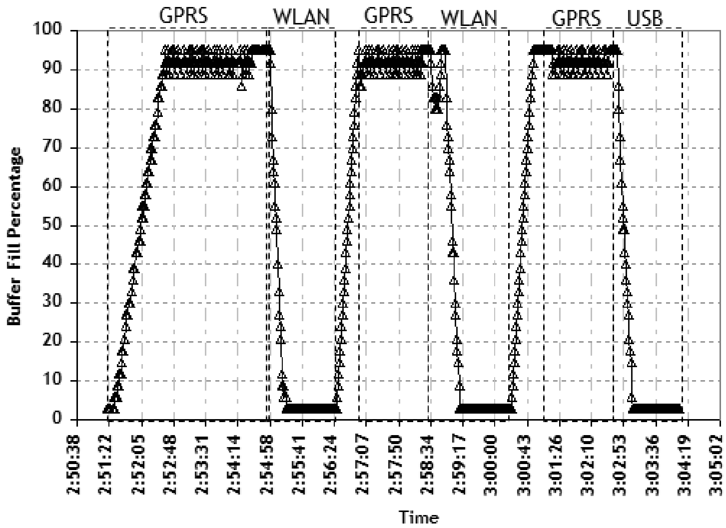

Figure 5.9: Monitoring device service buffer fill percentage vs. time for the generic monitoring profile (as measured on the MBU)

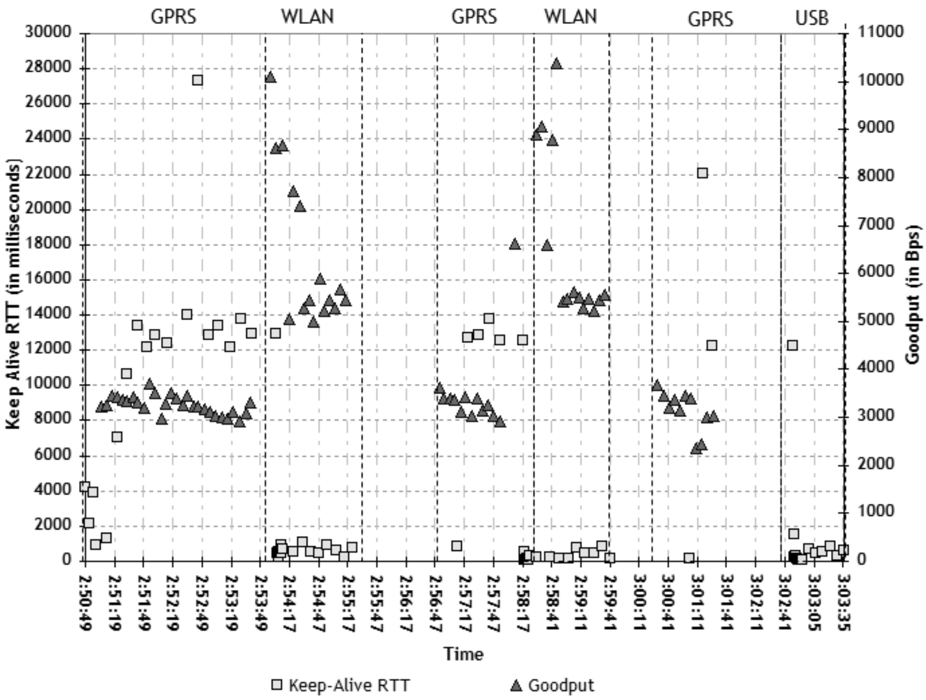

Figure 5.10: Biosignal data transfer goodput and Keep-Alive RTT vs. time for the generic monitoring profile (as measured on the surrogate host)

Figure 5.8 and Figure 5.10 also show the *RTT (in milliseconds) for keep-alive messages logged at the surrogate vs. time* for the cardio and generic monitoring profile respectively. The Keep-Alive RTT is in the order of a few hundred ms for the WLAN and fixed networks; however it is in the order of 10 seconds when connected to the GPRS network. These graphs also show high variance in the Keep-Alive RTT while the MBU uses a GPRS network. One of the reasons behind this behavior may be that the RTT depends (among others) on the load on the buffer fill level, this load in return depends on the current usage of the wireless network. As observed from the graph in Figure 5.10, before the transmission of biosignals the Keep-Alive RTT is below 5000 milliseconds. However, once the generation and transmission of biosignals begin, Keep-Alive RTT increases substantially.

Steady State Network Usage Performance

Since we observed a significant variance in the goodput and RTT during the biosignals transfer using the GPRS network, we conducted further experiments to observe these parameters for each network in the steady state (without any handovers). The data in Table 5.3 shows observed data transfer throughput in *bps* logged at the surrogate for the cardio and generic monitoring profiles. As can be observed from Table 5.3, the GPRS network provides around *20 kbps* data transfer throughput for the biosignals. Hence it is suitable for the monitoring profiles which produce biosignals at the rate of *20 kbps* or lower under the assumption that the buffers are big enough to cope with periods where the biosignals transmission requirement is higher than the available throughput. Compared to the GPRS network, WLAN and USB connections offer 26.1% and 25.6% higher average goodput for the cardio profile. These numbers are 77.1% and 77.6% respectively for the generic monitoring profile. Figure 5.11 shows results of Table 5.3 graphically.

Table 5.3: Biosignals data transfer goodput in bps (logged at the surrogate)

Network	***Cardio Profile***				***Generic Tele-Monitoring Profile***			
	Min (bps)	Max (bps)	Avg (bps)	Std Dev (bps)	Min (bps)	Max (bps)	Avg (bps)	Std Dev (bps)
GPRS	1104	29072	20616	2752	13936	26624	20887	1873
WLAN	19336	32432	26016	1417	26720	52648	36997	2294
USB	18152	46464	25903	3167	19816	56896	37096	3304

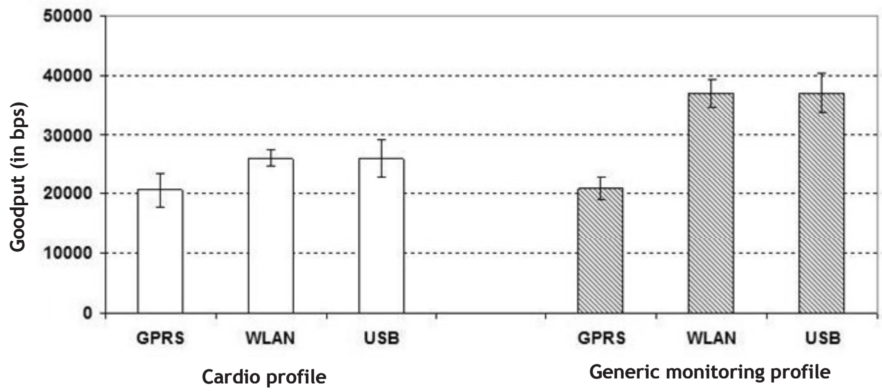

Figure 5.11: The graph showing average goodput during the steady measurement over the interval of 30 min. The white and shaded bars show the results for Cardio and Generic tele-monitoring signal profiles, respectively. The error bars on the top of the white and shaded bars represent the standard deviation.

For the steady-state observations, Table 5.4 shows the Keep-Alive RTT for the Cardio and Generic tele-monitoring biosignals profiles. As can be observed from this data, the GPRS network results in 24 times higher RTT than the WLAN network and 22 times higher RTT than the USB network. Figure 5.12 shows graphical representation of results listed in Table 5.4. The observed behavior of GPRS RTT matches with the experiments conducted in [Chak02] where it is concluded that GPRS RTTs are large and variable. Furthermore, it is also concluded in [Chak02] that the GPRS throughput is highly variable and fluctuates rapidly. This observation is similar to those for goodput in our case.

Table 5.4: Keep-Alive RTT in milliseconds (logged at the surrogate)

Network	***Cardio Profile***				***Generic Tele-Monitoring Profile***			
	Min	Max	Avg	Std Dev	Min	Max	Avg	Std Dev
GPRS	1060	33380	11410	5310	990	16260	11360	3680
WLAN	36	9500	560	1200	33	1050	360	220
USB	37	2830	560	320	49	2830	480	340

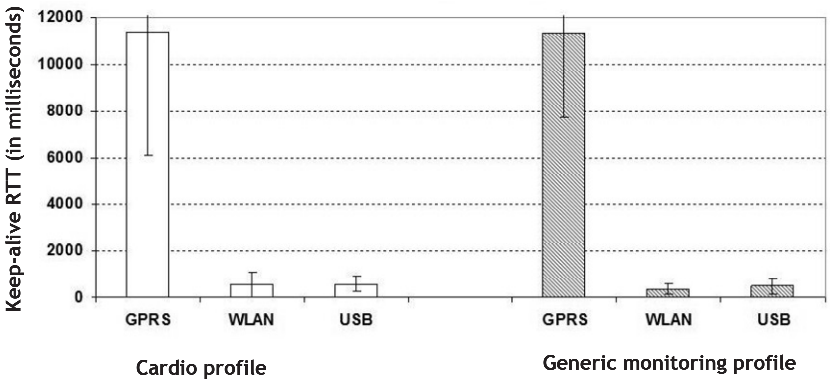

Figure 5.12: The graph showing results of the Keep-Alive RTT during steady measurement over the interval of 30 min. The white and shaded bars show results for the Cardio and Generic tele-monitoring signal profiles, respectively. The error bars on top of the white and shaded bars represent standard deviation.

5.5.3 Vertical Handover Performance Results

This section describes results of experiments conducted to measure the vertical handover performance. Table 5.5 and Table 5.6 show *networks involved in the handover*, *IP address configuration delay* D_t (minimum, maximum and average), *handover execution delay* D_e (minimum, maximum and average) and *total handover delay D* (minimum, maximum, average and standard deviation) for the cases of user handover and forced handover; respectively. The readings shown in Table 5.5 and Table 5.6 are averaged over 10 handovers between respective networks.

The data in Table 5.5 and Table 5.6 show that the *IP address configuration delay* is of the order of few hundred milliseconds. There is no significant difference in the IP address configuration delay between the user handover and the forced handover. The handover execution delay is of the order of seconds. A handover to the fixed network or WLAN network results in a handover execution delay of 2 - 5 seconds. However, a handover to the GPRS network results in an average handover execution delay of 21 seconds. Due to the behavior of operating system (Windows Mobile 2003 on the QTEK 9090 PDA) running on the MBU, while performing a handover to the GPRS network, the WLAN network can not be used by the MBU. Hence during that time, no biosignals data can be sent to the BESys.

The standard deviation of overall delay for the GPRS network is around 11.5 seconds, which shows similar behavior observed for the Keep-Alive RTT in Figure 5.8 and Figure 5.10. Though the results shown in this section are not conclusive enough because of a small sample size, a general trend is observed that the handover to the GPRS network involves considerably higher delays than the handover to the WLAN network. Figure 5.13 shows results in Table 5.5 and Table 5.6 graphically.

Table 5.5: IP address configuration delay, handover execution delay and total handover delay for the user handover (all numbers are in milliseconds)

Handover	**Min D_t (ms)**	**Max D_t (ms)**	**Avg D_t (ms)**	**Min D_e (ms)**	**Max D_e (ms)**	**Avg D_e (ms)**	***Min D* (ms)**	***Max D* (ms)**	***Avg D* (ms)**	***Std. Dev.* (ms)**
USB-WLAN	480	1300	740	1150	8040	1910	1680	14780	2650	2240
WLAN-USB	360	870	600	330	17500	3000	1070	18030	3600	5470
GPRS-WLAN	580	3720	1470	330	20630	3540	1300	21250	5010	6170
WLAN-GPRS	520	1660	870	2060	35540	9530	2580	36280	10400	11560
USB-GPRS	650	960	750	19630	29710	23390	20590	30350	24130	3480
GPRS-USB	480	890	670	550	1200	820	1190	1860	1490	280

Table 5.6: IP address configuration delay, handover execution delay and total handover delay for the forced handover (all numbers are in milliseconds)

Handover	***Min D_t* (ms)**	***Max D_t* (ms)**	***Avg D_t* (ms)**	***Min D_e* (ms)**	***Max D_e* (ms)**	***Avg D_e* (ms)**	***Min D* (ms)**	***Max D* (ms)**	***Avg D* (ms)**	***Std. Dev.* (ms)**
USB-WLAN	560	2870	1220	340	1310	920	1560	3210	2140	630
WLAN-USB	520	1500	930	720	6180	1950	1250	7280	2890	2220
GPRS-WLAN	450	1830	950	400	1350	800	830	3180	1750	720
WLAN-GPRS	420	850	670	5690	41850	30590	6390	42670	31260	12140

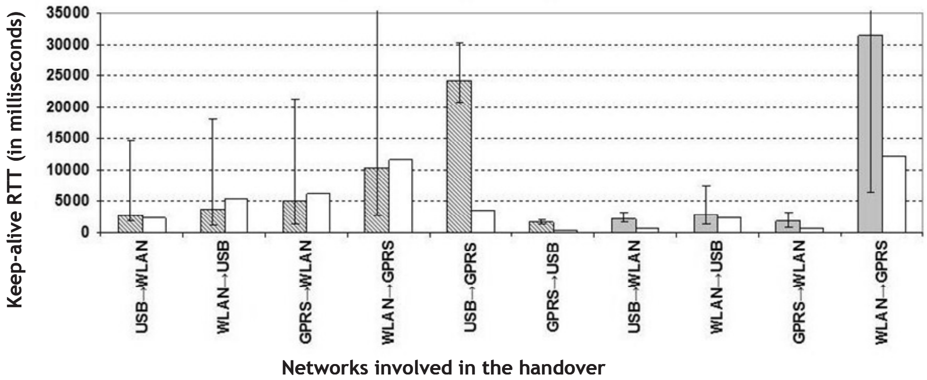

Figure 5.13: A graph showing average handover delay. The sample size for the user and forced handover is 10. Shaded, grey and white bars represent user handover delay, forced handover delay and standard deviation respectively. The error bars on the top of these bars represent the minimum and maximum handover delay.

5.5.4 System Resources Utilization

The graph shown in Figure 5.14 represents memory and CPU utilization of the MBU during one of the patient monitoring sessions. In the beginning, the memory utilization (solid line) is low and CPU utilization is high because of the initiation of the monitoring service. Once a device service connects to the BAN sensor set and starts sending data, the memory utilization increases and stabilizes at around 5 MB, of which the size of the monitoring service buffer is 1.5 MB. The CPU utilization (dashed line) is not significant at the later stage of the monitoring session.

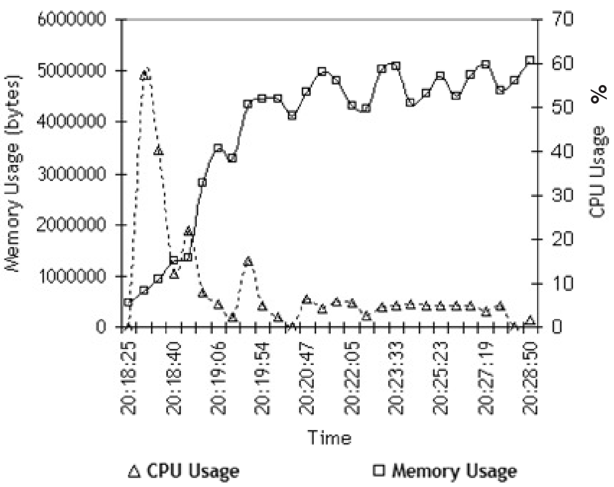

Figure 5.14: Memory and CPU utilization of the MBU during a mobile patient monitoring session

5.6 Conclusions

The research reported in this chapter is conducted to address research objective 2 of this thesis. The resulting context-aware mobile controlled handover (MCHO) approach provides HTTP connectivity to the MBU in the events of patient mobility and network outage provided that the MBU is capable of using alternate wireless network available at that location. The MCHO mechanism adds following components to the MHPMS: *communication context source, context processor* and *context reasoner*. All of these components run on the MBU. The communication context source provides information about types of wireless network to which the MBU is connected, IP address of MBU network interfaces and whether the network provides Internet connectivity. The context processor processes this information and the context reasoner takes a network selection decision. Since, in principle, a certain types of networks (e.g. WLAN) provide higher goodput and lower RTT compared to other types of networks (e.g. GPRS), the network interface selection criterion in the context reasoner always chooses the network with the maximum bandwidth capacity among the available ones. To take into account changes in the network availability, a handover decision making phase is initiated whenever a new wireless network is detected, or when the MBU disconnects from the current wireless network in use.

To measure the gains achieved by proposed MCHO mechanism, to quantify the overheads of the vertical handover (research objective 5) as well as to measure the resources usage of the MBU, we came up with the performance evaluation objectives of the following three types: 1) network performance in terms of the goodput, RTT and monitoring service buffer size; 2) vertical handover performance in terms of the handover triggering and handover execution delay; and 3) resource utilization in terms of the memory and CPU usage on the MBU. The experimental setup consists of a MHPMS test bed with the 802.11b, GPRS and USB connectivity. The experiment runs consisted of two types of handovers – user handover and forced handover as well as steady state network performance experiments. The experiments are conducted for two types of biosignals profiles (cardio biosignals profile – goodput requirements: 28472 bps and RTT requirements: 500 ms and generic monitoring biosignals profile – goodput requirements: 40554 bps and RTT requirements: 500 ms). The averaged results for the network performance are summarized in Table 5.7. The averaged values of handover related delays are shown in Table 5.8.

Comparing these results with the QoS requirements, it is observed that the GPRS network used during the experimentation does not satisfy either of the goodput or RTT requirements of the biosignals transfer. The WLAN network offers a better QoS performance, however it did not satisfy RTT requirements of the cardio profile. The fixed network provides similar performance to that of the WLAN network.

Table 5.7: Average steady state network performance results for the Cardio and Generic Tele-monitoring profiles. No handovers were performed during these experiments

Network	Cardio Profile		Generic Profile	
	Avg Goodput (bps)	Avg RTT (ms)	Avg Goodput (bps)	Avg RTT (ms)
GPRS	20616	11408	20887	11359
WLAN	26016	563	36997	362
USB	25903	563	37096	480

Table 5.8: Average values of the IP address configuration delay (*D_t*), handover execution delay (*D_e*) and total handover delay results for the user handover and forced handover (all numbers are in milliseconds)

	User Handover			***Forced Handover***		
Handover	Avg D_t (ms)	Avg D_e (ms)	*Avg D* (ms)	Avg D_t (ms)	Avg D_e (ms)	*Avg D* (ms)
USB-WLAN	740	1915	2655	1221	921	2142
WLAN-USB	604	3002	3606	933	1954	2887
GPRS-WLAN	1469	3539	5008	952	796	1747
WLAN-GPRS	875	9527	10402	668	30594	31262
USB-GPRS	747	23388	24135			
GPRS-USB	674	819	1492			

Overall, we observed that the GPRS network results in higher handover latency, provides lower goodput and higher RTT compared to the WLAN network and the fixed network. The handover triggering delay (D_t) is measured in terms of time required to configure a new IP address on the MBU and it represents overhead of components context processor and context reasoner which are introduced in this work. A handover execution delay (D_e) is influenced by delay characteristics of newly selected network, e.g. handover execution delay is the highest while handover to the GPRS network. The resource utilization is well within the limits of the MBU. Given these results, incorporating MCHO support within MHPMS is helpful to maintain HTTP connectivity to the MBU in the events of patient mobility and network outage. However the proposed MCHO support alone does not guarantee that the QoS requirements for the biosignals transfer are met.

The obtained results also show that compared to the access link bandwidth capacity, experienced goodput varies widely. E.g., for the GPRS network used, the uplink bandwidth capacity is 26 kbps; however, the obtained average goodput is 20.1 kbps. Hence, we think that the knowledge of actual values of goodput and RTT provided by the wireless network may prove more beneficial for use in the mobile patient monitoring systems. Given that QoS predictions are intended to provide actual values of QoS offered by wireless network, in Chapter 6 we extend the MCHO mechanism proposed herewith to make use of QoS predictions during the network selection process.

Chapter 6

Network Assisted Vertical Handover Mechanism[17]

Research objective 3 of this thesis is as follows: If information about the QoS characteristics of wireless networks at a given location and time are known, how to take a network selection decision for the continuous delivery of biosignals? It is proposed that these QoS characteristics are available in the form of QoS predictions [Wac09b]. In this chapter we illustrate a *context-aware network assisted handover* (NAHO) *mechanism* which, along with other context information uses QoS predictions to take a handover decision.

This chapter is organized as follows: Section 6.1 motivates the rationale behind proposed mechanism. Section 6.2 and Section 6.3 illustrate the architecture and detailed working of proposed NAHO mechanism respectively. Section 6.4 elaborates on performance evaluation objectives for the NAHO mechanism. Section 6.5 outlines simulation setup, simulation tools and implementation details. Section 6.6 discusses simulation experiment runs, results obtained and their interpretation. Section 6.7 concludes the chapter.

6.1 Introduction and Motivation

Recently, mobile devices equipped with location detection sensors such as GPS receiver and network performance measurement software such as *NetPerf* are being used for detecting availability of wireless networks and measuring QoS experienced by a mobile application. There is also an increasing willingness of users to share such data. E.g. a wireless geographic logging engine knows as WIGLE.NET[18] records information about 28 million (and growing) WiFi network installations contributed by its community members. The *QoS Information System* (QoSIS) [Wac09b] is also an

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[17] This chapter is based on our work published in [Pawa08c], [Pawa09a], [Pawa09b] and [Wac09a].
[18] http://www.wigle.net/

initiative that collects information about real-world QoS experienced by a mobile application in order to generate and provide *QoS predictions* to interested mobile applications. The QoS predictions consist of real-world QoS information offered by different wireless networks in the vicinity of a mobile device along following dimensions: *geographical location*, *time*, *wireless access network provider* and *wireless access technology*.

In order to design a vertical handover mechanism that addresses research objective 3, herewith we continue to follow context-aware computing based architecture similar to the MCHO mechanism. The justification behind the use of context-aware computing based architecture is provided in Section 5.1.3. In the state of the art chapter, the process of vertical handover management and applications of vertical handover are studied in details. In the vertical handover management process, it is the responsibility of a handover decision making phase to select a wireless network suitable for data transmission. In Chapter 3, we provided an overview of six vertical handover management approaches. The overview of these approaches is shown in Table 6.1.

Table 6.1: The overview of selected vertical handover management approaches

Parameter	***Bala04***	***Ahme06***	***Wu09***	***Chen05***	***Hong06***	***Vida05***
Handover level	Transport layer	Transport layer	Link layer	IP layer	Application layer	IP layer
Supported networks	LAN, WLAN, GSM, UMTS	LAN, WLAN, GSM, UMTS	WiFi, WiMAX	WLAN, GSM	WLAN, GSM	LAN, WLAN, GSM
Network information	Yes	Yes	Yes	Yes	Yes	Yes
Terminal information	Yes	Yes	No	Yes	Yes	Yes
User information	Yes	Yes	No	No	No	Yes
Application information	Yes	Yes	No	Yes	Yes	Yes
Decision algorithm	AHP	AHP	AHP + SAW/MEW	QoS comparison	QoS comparison	Policy based
Handover type	NCHO	NAHO	MCHO	NAHO	MCHO	MCHO
Practical validation	Yes	Yes	No	No	No	Yes

Based on the state of the art and following the handover management process proposed in [Kass08], in Chapter 4, we elicited context information requirements to address research objective 3. The vertical handover mechanism proposed in this chapter is designed to make use of this set of context information. These requirements are shown in Table 6.2.

Table 6.2: Context information requirements to address research objective 3

Information type	***Context Information***
QoS requirements context	Biosignals delivery QoS requirements (goodput and RTT based on the signal profile of the monitoring service
Communication context	A list of wireless networks along with provider names, technologies, maximum uplink bandwidth and delay in the surroundings of a mobile device (details in [Pedd05, Pedd07]).
QoS-Predictions Context	All available wireless networks as specified by provider names, network names and technologies along with their coverage ranges and availability at a given location/time and predicted QoS information (goodput and RTT). (details in [Wac06, Wac08, Wac09b])
Location and Time context	Coordinates of the device's current geographic location (longitude, latitude) and time (Date, HH:MM:SS).

One of the primary concerns to address research objective 3 is the choice of a handover decision making algorithm. It is observed from Table 6.1 that among six vertical handover approaches, three approaches [Bala04, Ahme06, Wu09] use *analytic hierarchy process* (AHP) in the decision making process. The QoS comparison based decision making in [Chen05] simply selects a wireless network that closely satisfies application's QoS requirements. The QoS comparison based decision making in [Hong06] performs a normalization procedure to compare the upper and lower bounds of offered QoS and required QoS in three classes which are: -1, 0 and 1; respectively. The handover decision making is activated if the class of one of the upper or lower bounds is -1. In comparison, the AHP algorithm is used in [Bala04, Ahme06] to select a wireless network that maximizes application's bandwidth requirements and minimizes delay and loss requirements. Thus, the decision making in [Bala04, Ahme06] also attempt to satisfy application's QoS requirements. Looking at the practical validation aspect of vertical handover management approaches, Table 6.1 shows that the AHP based decision making in [Bala06, Ahme06] is validated on the personal mobile devices (which functions as a MBU in a mobile patient monitoring system) while the QoS comparison approaches in [Chen05, Hong06] are simulated.

In the research literature, a number of handover decision making algorithms have been proposed, compared and evaluated. E.g. *multiplicative exponent weighting* (MEW), *simple additive weighting* (SAW), *technique for order preference by similarity to ideal solution* (TOPSIS) and *analytic hierarchy process combined with grey relational analysis* (AHP+GRA) [Stev06]. These algorithms are proposed for following application data traffic classes: *conversational* (e.g. voice traffic), *streaming* (e.g. streaming video), *interactive* (e.g. web browsing) and *background* (e.g. email) [Dixi01]. A simulation based comparison of decision making algorithms in [Stev06] show that the MEW, SAW and TOPSIS provide similar performance for all the above four traffic classes, while AHP+GRA provides slightly higher bandwidth and lower delay for the interactive and background traffic classes. Since the practical evidence of AHP based handover decision making on the handheld mobile devices is available and AHP is found to provide at par performance with other decision making algorithms [Stev06], we choose to use AHP for handover decision making in the mechanism proposed in this chapter.

In the vertical handover management process described in [Chen05], the wireless network QoS information provided by an entity named *Location Service Server* (LSS) is used to take a handover decision. Since the LSS is assumed to be located in the Internet, the vertical handover technique used in [Chen05] is classified as *network assisted vertical handover* [NAHO] approach. Functionally, both, the LSS and QoSIS are equivalent, as both of them provide real-world QoS information of wireless networks. Motivated from this, herewith we propose a *context-aware network assisted handover* (NAHO) *mechanism* that uses QoS predictions for handover decision making.

Since the real operational context source providing QoS predictions is unavailable, we adopt a simulation based approach for evaluating proposed NAHO mechanism. To simulate real-life uneven geographic placement of wireless networks and to provide QoS predictions context information, we built a *QoS Context Source Simulator*. To model real-life movements of a patient, we built another simulator named *User Trip Simulator*. Both of these simulators are based on *Service Oriented Architecture* (SOA) and they advertise themselves as a context source service in the simulated experimental setup. The simulation compares gains and overheads of proposed NAHO mechanism with respect to the MCHO mechanism and *wireless wide area network* (WWAN) only mechanism. There are no handovers involved in the WWAN only mechanism and the MBU is assumed to have Internet connectivity using WWAN network (e.g. GPRS).

6.2 Architecture of the NAHO Mechanism

Figure 6.1 shows proposed architecture of the NAHO mechanism. Since the QoS predictions service is hosted in the Internet, in the NAHO mechanism architecture, this component is shown in the fixed network. The elements within the dotted boundary are introduced newly in the MHPMS..The description of BAN sensor set, monitoring device service, message worker and stream worker components is given in Section 2.6.

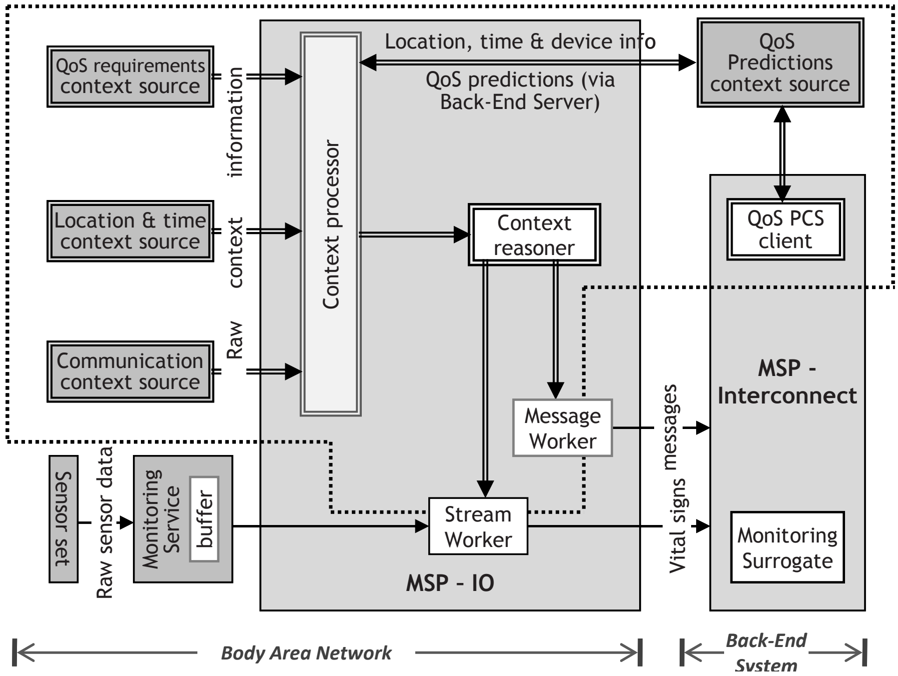

Figure 6.1: Architecture of the NAHO Mechanism with the context sources placed at both, the MBU and fixed network

The context sources (CS) hosted on the MBU are *QoS requirements CS*, *user preferences CS*, *location & time CS*, *communication CS* and *device CS*. The *QoS predictions CS* is hosted in the fixed network. A brief description of these context sources and motivation behind their selection is presented in Table 6.3. The context sources on the MBU are modelled using a principle of nomadic mobile context source. As illustrated in [Halt06], a *nomadic mobile service* is a service oriented computing based service offered by an Internet capable mobile host such as a handheld device, mobile phone or an embedded device. The service provided by a mobile host is registered in the service registry so that the client located anywhere in the Internet is able to find and bind to it. A nomadic mobile service may also act like a *nomadic mobile context source* that offers the following three types of methods [Pawa07d]:

1. *getContext()* allows a client to obtain context information.
2. *subscribeContext()* allows a client to subscribe for the context updates. The client should provide a callback interface over which the context change notification is sent.
3. *unsubscribeContext()* allows a client to cancel subscription for the context updates.

Table 6.3: Brief description of the context sources used in NAHO mechanism

CS Name	*Handover Information*	*Motivation*
Location & Time CS	Coordinates of the device's current geographic location (longitude, latitude) and time (Date, HH:MM:SS) as obtained from the GPS receiver.	It is observed that the availability of and QoS offered by the wireless networks is dependent on the location and time. (details in [Wac06, Wac08])
Communication CS	A list of wireless networks along with provider names, technologies, maximum uplink bandwidth and delay (Network Cross Layer Info. in XML) in the surroundings of a mobile device (details in [Pedd05, Pedd07]).	To get an IP address assigned to the mobile device network interface by the network operator.
QoS requirements CS	Biosignals delivery QoS requirements. The goodput is based on the signal profile of the monitoring service. The delay is based on the type of application domain that determines delay	As observed in [Pawa07b, Pawa08b], depending on the signal profile and purpose of patient monitoring, the biosignals delivery has associated QoS requirements.
QoS-Predictions Context Source (QoSCS) [Wac06, Wac08]	All available wireless networks as specified by provider names, network names and technologies along with their coverage ranges and availability at a given location/time and predicted QoS information (goodput and RTT) as a function of location and time.	This information is used in the proposed mechanism to obtain availability and QoS information of the wireless networks along the user's mobility path.

The *context processor* and *context reasoner* components are implemented as separate components from the existing implementation of *Mobile Service Platform – IO* (MSP - IO), however in order to change the network interface IP address used in *message worker* and *stream worker*, these components are packaged together with MSP-IO. The role of MSP in the MHPMS is illustrated in Section 2.6. A context processor requests QoS predictions via the surrogate host that also hosts a client to the QoSCS. The *Context Reasoner* is also developed as a part of MSP-IO. It uses context information obtained from the context processor for dynamic selection of and handover to the wireless network that closely satisfies QoS requirements of biosignals delivery. A detailed working of NAHO mechanism is provided in the following section.

6.3 Detailed Description of the NAHO Mechanism

Similar to the MCHO mechanism illustrated in Chapter 5, in the NAHO mechanism, a context processor is responsible for the handover information gathering phase and a context reasoner is responsible for the handover decision making phase and initiating the handover execution phase. The design of these components is shown using flowcharts. The symbols used in these flowcharts are shown in Figure

6.2. The hierarchical structure of QoS predictions proposed in Section 4.3.1 is repeated in Figure 6.3 for a quick reference.

Figure 6.2: Flowchart symbols used for the illustrations

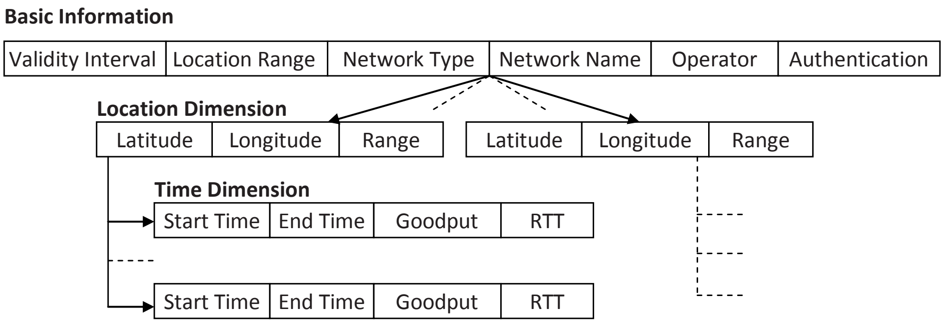

Figure 6.3: Hierarchical structure of QoS predictions (see also Section 4.3.1)

6.3.1 Context Processor

The role of a *Context Processor* (CP) component is to retrieve context information from the context sources, generate a *context snapshot* and provide this context snapshot to the context reasoner for making a network selection decision at a given location and time. Figure 6.5 shows a flowchart depicting working of a context processor. The following concerns have been taken into account while designing the context processor component:

1. Obtaining context information from the context sources;
2. Subscribe to context changes;
3. Preparing the context information to send to the context processor;
4. Processing context changes;
5. Requesting QoS predictions from the MBU;
6. Storing QoS predictions on the MBU;
7. Processing QoS predictions to determine wireless networks at the current location of MBU;
8. Processing QoS predictions to obtain wireless networks QoS values at the current time;
9. To determine the location at which to request a new set of QoS predictions;
10. To determine the time at which to request a new set of QoS predictions;
11. Ensuring that the QoS predictions request is sent whenever a new set of QoS predictions is required.

Herewith, we assume that the QoS predictions service is available when needed. The issues related to unavailability of QoS predictions are described in the Future Work. The flowchart showing the working of context processor component is shown in Figure 6.5.

We use a new terminology called *context snapshot* to denote the piece of context information sent from the context processor to the context reasoner component. The context snapshot represents information used by a context reasoner component for taking a network selection decision using QoS predictions. The QoS predictions useful at a given location and time combined with QoS requirements for biosignals delivery together form a *context snapshot*. The inclusion of QoS requirements in the context snapshot allows a context reasoner to take a weighted decision on the selection of wireless network to handover to. Figure 6.4 shows the structure of a context snapshot.

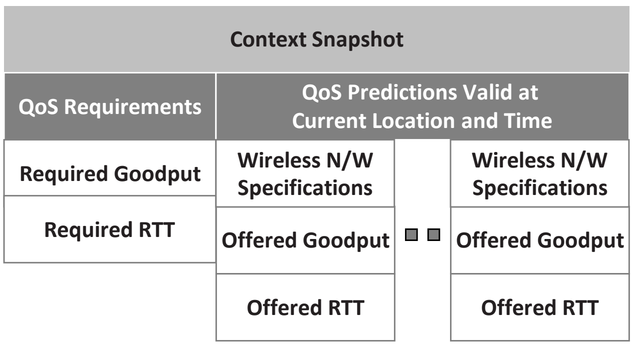

Figure 6.4: The structure of a context snapshot

Requesting QoS predictions

The QoS predictions are required to construct a context snapshot. However, since the QoS predictions CS is hosted in a fixed network, the context processor requests QoS predictions on the activation of monitoring device service. The interactions between the context processor and QoS predictions CS are as follows:

1. Upon activation of the monitoring device service on the MBU, the CP obtains current location and time from the location & time CS and provides this information to the QoSCS to obtain QoS-predictions.
2. The CP uses the *Surrogate Host HTTP Connection* to request QoS-predictions using a MSP request-reply message referred to as *GET_QOSPREDICTIONS*. The message parameters include *location (latitude, longitude)* and *time* at the mobile device. It is assumed that this information is obtained from the GPS receiver.
3. The *GET_QOSPREDICTIONS* message is received by the surrogate host which initializes a client to forward this message to the QoSCS.

4. Along with the QoS-predictions, the QoSCS returns the QoS predictions in the format shown in Figure 6.3 to the requesting client.
5. As per the MSP implementation, the QoS predictions are sent to the CP in a HTTP reply to the *GET_QOSPREDICTIONS* message.
6. The CP extracts wireless network availability and their provided QoS information from the received predictions and stores this information locally on the MBU.
7. Since the QoS predictions are valid for a limited amount of time, the CP locally sets a timer named as *predictions validity timer* to request predictions a few seconds[19] before the validity interval of QoS predictions expires.
8. The CP performs mathematical calculations[20] to determine wireless networks at current location and to extract the values of offered QoS by them. This constitutes the QoS predictions part of context snapshot.
9. Due to the patient mobility, a patient may wander out of the *locations range* of QoS predictions. The locations range represents a distance between the farthest network from the current location of mobile device. Hence, the CP also has a mechanism to request new predictions when the user is on the boundary (within certain distance) of locations range, so that the QoS predictions for that location be already available.

Practical issues with obtaining QoS predictions

There have been following issues with obtaining QoS predictions in an experimental setup. The QoS predictions may contain information about multiple wireless networks contributing to its size. Initially, from the CP, we tried to request predictions based on a predefined range (e.g. `500m`). However, in case of a densely populated area (e.g. `Manhattan`) with many wireless networks, the prediction information can consist of a huge number of networks (e.g. `120 networks`). Sending information from the surrogate host to the MBU involves message encoding operation on the surrogate host and message decoding[21] operation on the MBU. These operations are performed by the *MSP-Interconnect* and *MSP-IO* packages respectively. Encoding a large amount of QoS predictions caused exceptions during the experiments. The optimal maximum size of QoS predictions is found to be around 34 kb[22]. The QoS predictions of this size contain predictions about 30 wireless networks. For the experimentation reported in this chapter, the validity period of QoS predictions (*validity interval*) is 30 minutes.

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[19] This value was configured to 3 seconds during the experiments.
[20] These calculations are according to the *Geographic Calculation Library* (available at http://www.zipcodeworld.com) that implements methods to calculate the distance between a pair of location coordinates.
[21] These operations are implemented as part of the nl.utwente.msp.message package.
[22] See Table 6.3 for details.

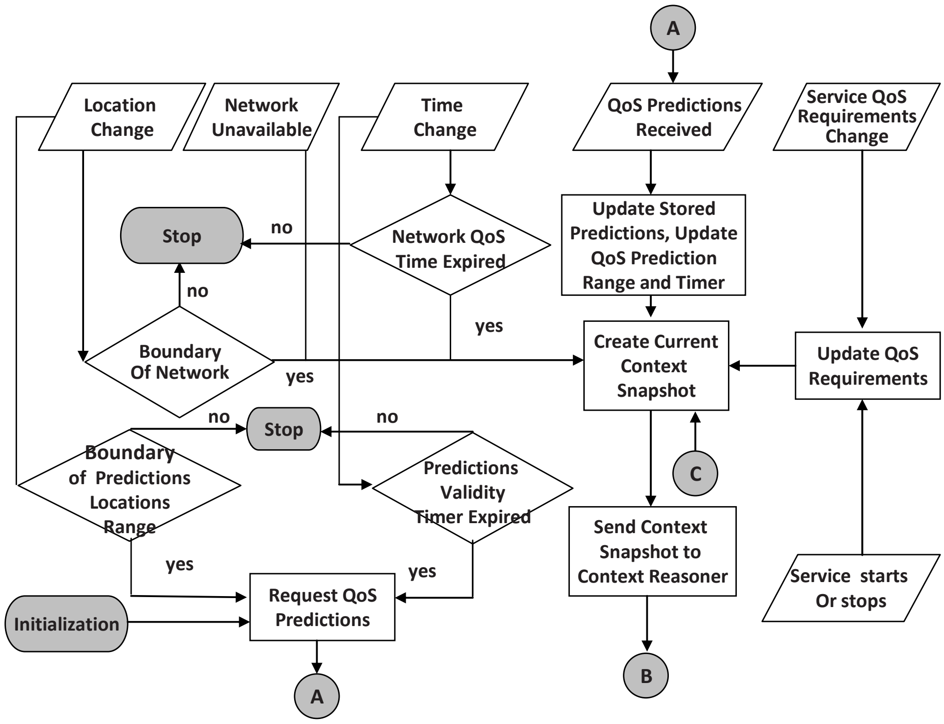


Figure 6.5: Flowchart showing the working of context processor component

Handling context changes

In order to obtain the latest available context information, the context processor subscribes to the context sources using the *subscribeContext()* method. The information obtained from the individual context sources is useful to determine following context changes: *location change, network unavailability, time change, receiving QoS predictions* and *change in the service's QoS requirements*. It is necessary to process these changes so that the context snapshot representing latest context information can be sent to the context reasoner. These context changes are processed as follows:

1. *Location change*: When a user location changes, there are two conditions of concern: 1) The user is on the boundary of the network currently in use; 2) The user is on the boundary of predictions locations range. In the first case, a new context snapshot is created. In the second case, new QoS predictions are requested. The location information is updated every second by the GPS receiver; hence the calculations to determine above conditions are performed every second.
2. *Time change*: When the time change occurs, there are two conditions of concern: 1) The validity of offered QoS of the current network has expired;

or 2) The predictions validity timer of QoS predictions is about to expire. In the first case, a new context snapshot is created. In the second case, new QoS predictions are requested. Since the time information is updated every second by the GPS receiver, hence the calculations to determine the above conditions are performed every second.

3. *Network unavailability*: This event is triggered when the network currently in use becomes unavailable, either due to patient moving out of the range of wireless network or the network outage. In this case a new context snapshot is created. The network unavailability is the event which is also addressed by the NAHO mechanism.
4. *New QoS predictions received:* Whenever new QoS predictions are received on the MBU, the stored predictions are updated and predictions validity timer value and location range values are updated on the MBU.
5. *Change in services QoS requirements:* In this case, service's QoS requirements are updated and a new context snapshot is created.

6.3.2 Context Reasoner - Analytic Hierarchy Process Based Handover Decision Making

The role of a context reasoner component is to perform AHP based network selection procedure on the context snapshot received from a context processor. As illustrated in Section 6.1, the handover decision making algorithm chosen for network selection is *Analytic Hierarchy Process* (AHP) [Saat90]. In order to select a wireless network that closely satisfies biosignals delivery QoS requirements, the AHP is applied on the QoS requirements and QoS predictions received in the context snapshot to satisfy the following optimization objectives:

1) *Goodput objective:* Satisfy monitoring service's goodput requirements; and
2) *RTT objective:* Satisfy monitoring service's RTT requirements.

These objectives are chosen because of the following reasons: 1) The QoS requirements of biosignals delivery are represented in terms of the goodput and the RTT. 2) The QoS predictions are proposed to provide goodput and RTT information as part of the wireless network QoS information. However, as will be shown in Chapter 7, the proposed AHP algorithm can consider additional objectives for the network selection. As described in [Saat90], AHP is about dividing a problem into several sub-problems and later aggregating solutions of these sub-problems into a conclusion. Based on the information received in the current context snapshot, the CR applies the following steps as per the AHP:

1) *Decide the relative importance of optimization objectives;*
2) *Compute relative weight of each available network for each objective by considering QoS requirements of biosignals delivery and QoS provided by wireless networks;*
3) *Calculate overall score for each network and select the network having the highest score for handover execution.*

These steps are explained in the following.

Step 1: *Decide the relative importance of the goodput and RTT optimization objectives*. The relative importance of an optimization objective is represented by a weight assigned to it. As per the AHP, the combined sum of all the objective weights is always 1. By assuming that the goodput objective and RTT objective are equally important, for the experimentation, the weights of the goodput objective and delay objective is assigned to 0.5[23] each.

Step 2: *Compute the relative weight of each available network for each of the objectives:* This step consists of the following sub-steps:

a). For each of the two objectives, assign a score on the scale from 1 to 9 to each pair of the available networks for creating a *pair-wise comparison matrix* P_{ij}. For a *network pair* (N_1, N_2), a value 1 means that the network N_1 is *equally important* to network N_2. The score of value 5 (9) means that the network N_1 is *strongly (absolutely) more important* than network N_2. The *score* (N_2, N_1) is an inverse of *score* (N_1, N_2). This score scale is shown in Table 6.4.

Table 6.4: Explanation of AHP score scales

Score scale	***Comparison Description***
1	Network N1 and network N2 are of equal importance.
5	Network N1 is strongly more important than network N2.
9	Network N1 is absolutely more important than network N2.

For the goodput objective and RTT objective, we assign these values to the pair of network depending on how well *each network satisfies goodput* and *delay requirements* of the biosignals delivery. As an illustration, for the goodput requirement of *30 kbps*, a network N1 is equally important to N2 if both of them provide higher goodput than the *required goodput*. Continuing the same goodput requirements, the network N1 is strongly more important than N2 if N1 provides higher goodput than N2, though both of them may provide lower goodput than *30 kbps*. The network N1 is absolutely more important than N2 if N1 provides higher goodput than *30 kbps,* but N2 provides less goodput than *30 kbps.* These cases of N1, N2 and goodput requirement of *30 kbps* are shown in Figure 6.6. After adding a third network N3 offering the goodput of 30 kbps, the resulting pair-wise comparison values are shown in Figure 6.7.

[23] In the implementation of context reasoner, it is possible to vary the weights of AHP optimization objectives.

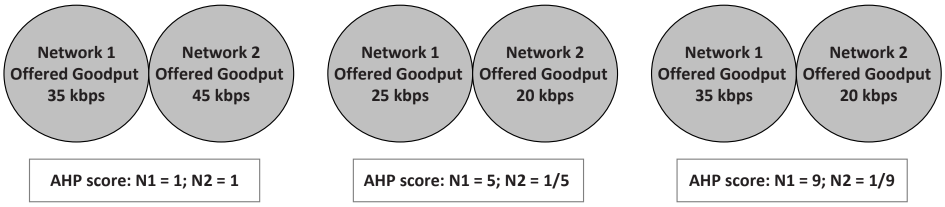


Figure 6.6: Calculating pair-wise comparison values of two networks N1 and N2 for the goodput objective based on their offered goodput and goodput requirement of 30 kbps

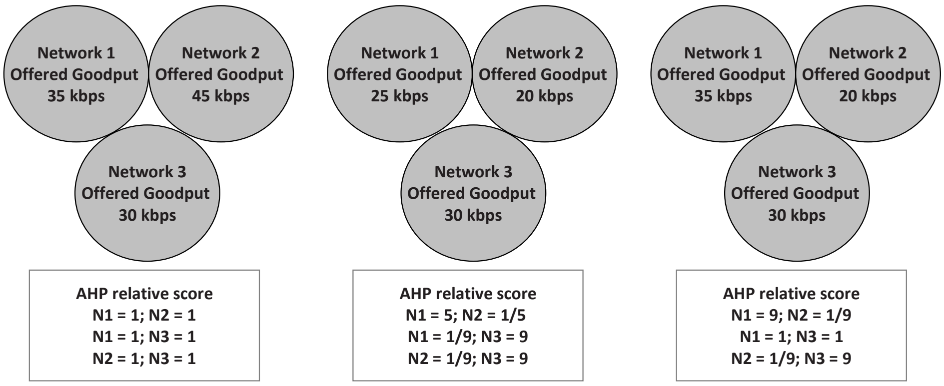


Figure 6.7: Calculating pair-wise comparison values of three networks N1, N2 and N3 for the goodput objective based on their offered goodput and goodput requirement of 30 kbps

b). For each of the optimization objective O_i, normalize each P_{ij} (divide by the sums of the columns) and average across rows to obtain the relative weights of the networks W_{no}.
Considering a set of three networks shown in Figure 6.7 offering goodput of 35 kbps, 20 kbps and 30 kbps respectively, a *pair-wise comparison matrix*, *normalized weight matrix* and *network weights* are shown in Figure 6.8.

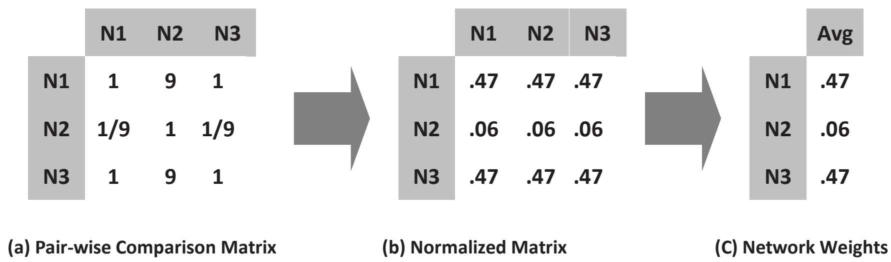


Figure 6.8: AHP calculation example

Step 3: *Calculate an overall score for each network and select a network with the highest score:* The overall network score is a sum of relative network weights multiplied by an objective weight. The most optimal network is the network with the highest overall score.

In the example shown in Figure 6.8, two networks N1 and N3 have the same score. In this case the network selected is N3 because goodput offered by the network N3 (30 kbps) closely matches service's goodput requirements compared to the goodput offered by network N1 (35 kbps).

6.3.3 Handover Execution Phase

The flowchart showing a handover decision making phase and handover execution phase is shown in Figure 6.9. The context processor and handover execution algorithms collaborate/interact at the points labelled *(B)* and *(C)* shown in Figure 6.5 and Figure 6.9 respectively.

Dwell Timer to Avoid Unnecessary Handovers

Two of the possible vertical handover scenarios involve a handover from a WWAN network (e.g. GPRS) to a WLAN network (e.g. WiFi) and from one WLAN network to the other WLAN network. These scenarios are shown in Figure 6.10 and Figure 6.11 respectively. In these scenarios, if the WLAN network to handover to serves a smaller geographic area and the user speed is sufficiently high, it is possible that the user just passes the WLAN network without benefiting from the handover. Such handovers are called *unnecessary handovers*.

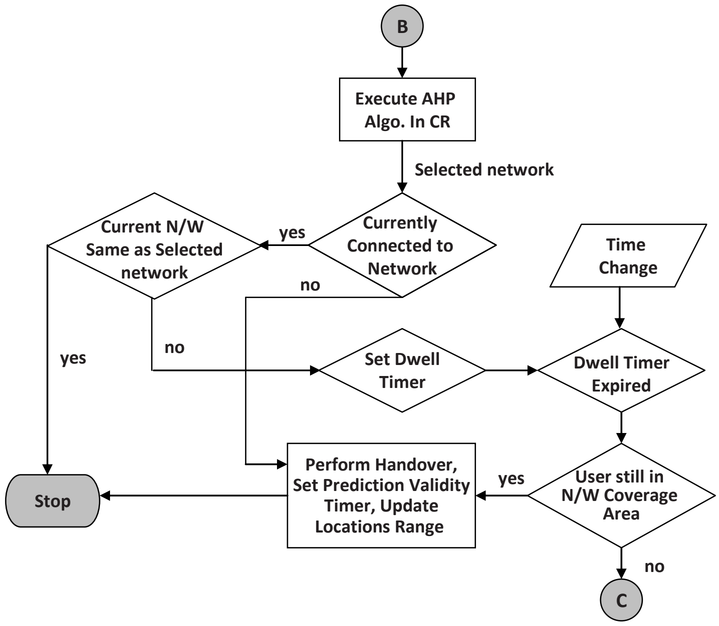


Figure 6.9: Flowchart showing handover decision making and handover execution phases

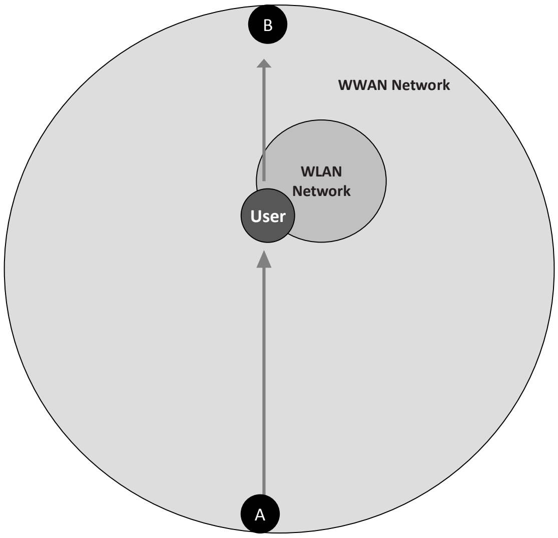


Figure 6.10: Example of an unnecessary handover while the user is connected to a WWAN network and moves towards the area covered by a WLAN network

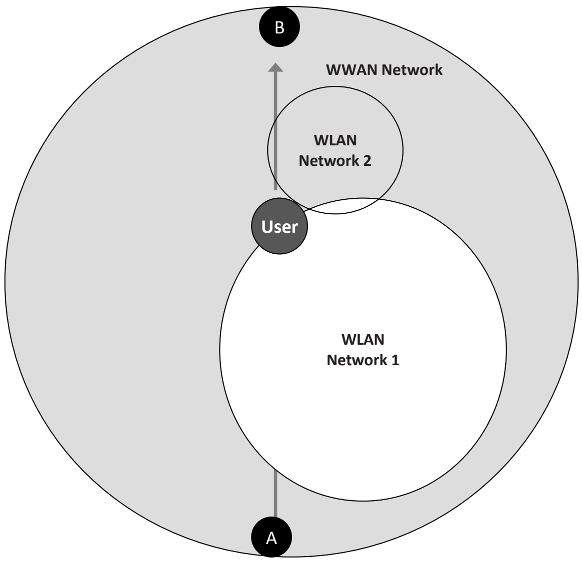


Figure 6.11: Example of an unnecessary handover while a user is connected to one WLAN network and moves towards an area covered by another WLAN network

To avoid these types of situations, a *dwell timer* concept similar to [Hong06] is applied. The dwell timer refers to an extra time spent in waiting for verifying the steady state condition of the wireless networks surrounding the MBU. If after the expiry of dwell time, while the user is on the move, if the network to handover to is still available, then the handover is executed, otherwise the AHP procedure is invoked again. Previously, researchers have used dwell timers with fixed value, e.g. 60 seconds in [Hong06], which is justified as the time spent in travelling *1 km* at the speed of *60 km/h*. However, in the network environment we consider that the radius of the WiFi network is smaller than *1 km*. Because of the availability of QoS predictions on the MBU, the network coverage area information is available to the context reasoner. Hence we choose the following parameters to determine the value of dwell timer:

1. *User speed*: The user speed based dwell timer is assigned a value equal to the time required to move out of the coverage area of WLAN network based on current user speed.
2. *Handover latency*: Handover latency is the amount of time elapsed between the network selection and start using the network for the data transfer. During this period, the remote monitoring service is still generating biosignals data. The benefits of handover can only be realized if after the handover, the data sent to the service buffer during the handover latency can be transmitted by the connected network. Hence, the dwell timer value based on the handover latency is the time required by a network to transmit biosignals data written in the se*rvice buffer during the handover*.

The selected value of a dwell timer herewith is the lower of the dwell timer values computed based on the user speed and the handover latency. When the dwell timer expires, if a user is still in the coverage area of selected network, then the handover is performed; otherwise the AHP algorithm is applied to a new context snapshot.

6.4 Simulation Based Performance Evaluation Parameters

In this section, we consider in detail the performance metrics that form the basis for comparing the NAHO mechanism with the MCHO mechanism. Due to the use of QoS predictions and AHP based network selection, it is expected that the NAHO mechanism provides higher extra-BAN communication QoS to the monitoring service as compared to the MCHO mechanism. To get an estimate of QoS values provided by a selected wireless network, we include *network performance objectives*. Since the NAHO network selection mechanism works differently than the MCHO network selection mechanism, we include *disconnection time* and *number of handovers* as the handover performance objectives. In addition to these, we also record the number of QoS prediction requests originating from the MBU.

6.4.1 Network Performance

To get an estimate of goodput and delay provided by a selected wireless network, we include the following network performance parameters similar to those in Section 5.3. The additional parameter included herewith is *biosignals data loss* as it helps to compare the amount of data loss by using the NAHO mechanism.

- *Biosignals Delivery Goodput:* This is the amount of biosignals transferred for a given biosignals profile using a wireless network selected during the handover.
- *Keep-alive RTT:* The Keep-alive RTT is an observed round trip time of the extra-BAN communication path between the MBU and the surrogate host.
- *Monitoring Service Buffer Fill Level:* Since the monitoring service buffer fill level is an indicator of the number of biosignal data packets awaiting their transmission, it is also one of the indicators of goodput. The lower the buffer fill level, the higher is the goodput.
- *Biosignals Data Loss:* This is the amount of data lost over the simulation period. Data loss occurs only when the monitoring service buffer is full and can't accommodate more data. As described in Section 2.6, when the packets accumulated in the buffer exceed a certain configurable *threshold* value, then older biosignals packets are removed to accommodate newer biosignals packets. The values of data loss reported herewith are not an indicator of data loss during the MHPMS system trials because there are no patients involved in the conducted experiments. The experimental setup considered herewith is not an indicator of practical setup required for medical trials of patient monitoring systems.

6.4.2 Vertical Handover Performance

The vertical handover performance parameters described in Section 5.3 include *delay for configuring a new IP address* and *handover execution delay*. However, since the NAHO mechanism is evaluated using simulations, the above parameters can not be measured due to the absence of a real operational system in the evaluation. However, the performance evaluation of the MCHO mechanism described in Chapter 5 already provided us the average estimates for the above delay. To compare the NAHO mechanism with the MCHO mechanism in the simulation environment, we came up with the following vertical handover performance parameters:

- *Disconnection time:* The time for which there is no network connectivity available to the MBU. Note that the disconnection occurs in the following cases: 1) The Mobile devices moves out of the coverage area of WLAN network; 2) During the handover execution phase.
- *Number of handovers:* This is the number of handovers experienced by both of the MCHO and NAHO network selection mechanisms over the duration of simulation run.

- *Number of QoS-predictions requests:* This parameter represents the number of requests sent by the context processor component to the QoSCS to obtain QoS predictions from the QoS context source[24].

6.5 Simulation Setup and Implementation Details

As explained in Section 6.1, it is not possible to evaluate the NAHO mechanism in a real operational system. Hence we chose to conduct simulations for the evaluation. To simulate the QoS predictions CS, we built a *QoSCS simulator*. To simulate patient's movements, we built a *user trip simulator*. Compared to the traditional simulation methodologies, these simulators take on a *close-to-real life* approach towards the simulation of WLAN network locations and user movements respectively. A QoSCS simulator is described in Section 6.5.1. A user trip simulator is illustrated in Section 6.5.2. The simulation parameters and experiment runs are described in Section 6.5.3.

6.5.1 QoS Context Source Simulator

For the evaluation of vertical handover mechanisms using simulations, previous research (e.g. [Chen05]) have assumed areas like square planes and WLAN base stations distributed randomly or uniformly in the square plane. However, in real life scenarios, such situations rarely occur. To model the location of WLAN base stations as realistic as possible, we rely on the observation that nowadays most of the businesses and institutes are covered by WLAN. We also observe that there is an increasing trend in urban environments to deploy high capacity WLANs installed by one operator covering large geographic areas (e.g. city centre). Moreover, a large number of private WLAN deployments may allow others to use their access network (without requiring authentication). Thus, potentially these wireless networks can be used by any user carrying a mobile device with appropriate network interfaces. In designing the QoSCS simulator, we can take advantage of this fact and of the availability of accurate location listings of businesses and institutes in the Internet (in our case as made available via *Google maps server* http://maps.google.com). As compared to the random distribution of WLANs in the square planes, the QoSCS simulator employs an approach of using the locations of businesses and institutes to assign WLAN base stations. To consider an aspect that the businesses and institutes maybe are spread over a larger geographic area, a WLAN is assigned coverage radius randomly between 10m and 300m. These parameters are configurable in the QoSCS simulator.

[24] The statistics showing the size of QoS predictions requests is elaborated further in Section 6.6.3.

A Sample URL of a HTTP Request to the Google Maps Server

Figure 6.12 shows a sample URL of a HTTP request to be sent to the Google maps server to obtain location and information about businesses. A typical response to such request from the Google maps server provides location and information of 10 requested business types closest to the specified location. If a larger number of businesses is required, then the value of a parameter named *start* in this URL should be incremented by 10 to request information about the further 10 closest businesses. Based on this observation, the property file of the QoSCS simulator consists of a number of values for these parameters. The other configurable parameters considered by the QoSCS simulator are shown in Table 6.5.

Table 6.5: Configurable parameters and values assigned to them in the QoS CS Simulator

Parameter	***Value***	***Justification***
Max WLAN goodput	55000 bps	These values are based on the experiments conducted with a real-life setup as reported in Chapter 5.
Min WLAN goodput	10000 bps	
Max GPRS goodput	25000 bps	
Min GPRS goodput	10000 bps	
Min WiFi delay	35 msec	
Max WiFi delay	1000 msec	
Min GPRS delay	1000 msec	
Max GPRS delay	25000 msec	
Max WiFi radius	300 meters	This number is introduced to take into account organizations and institutions spreading over a large geographic area. Nowadays, there are long range WLAN base stations available as reported in [Viva04].
Min WiFi radius	10 meters	This represents conventional WLAN routers available in the market.
Number of networks in QoS predictions	30	We came up with this number so that not to cause String encoding problems in MSP.
Time of predictions	30 minutes	We need to do additional experiments to find out the optimal time of predictions. Presently, we keep it as 30 minutes so that not to send too many QoS prediction requests to the QoSCS.

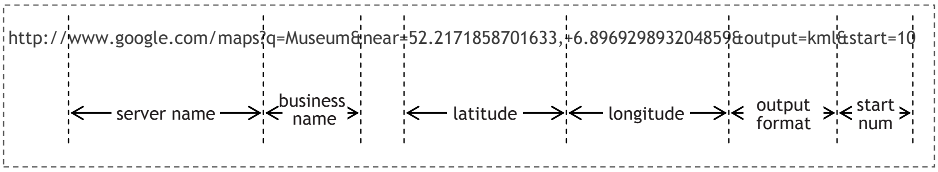


Figure 6.12: Sample URL of a HTTP request to obtain a list of museums around a particular location

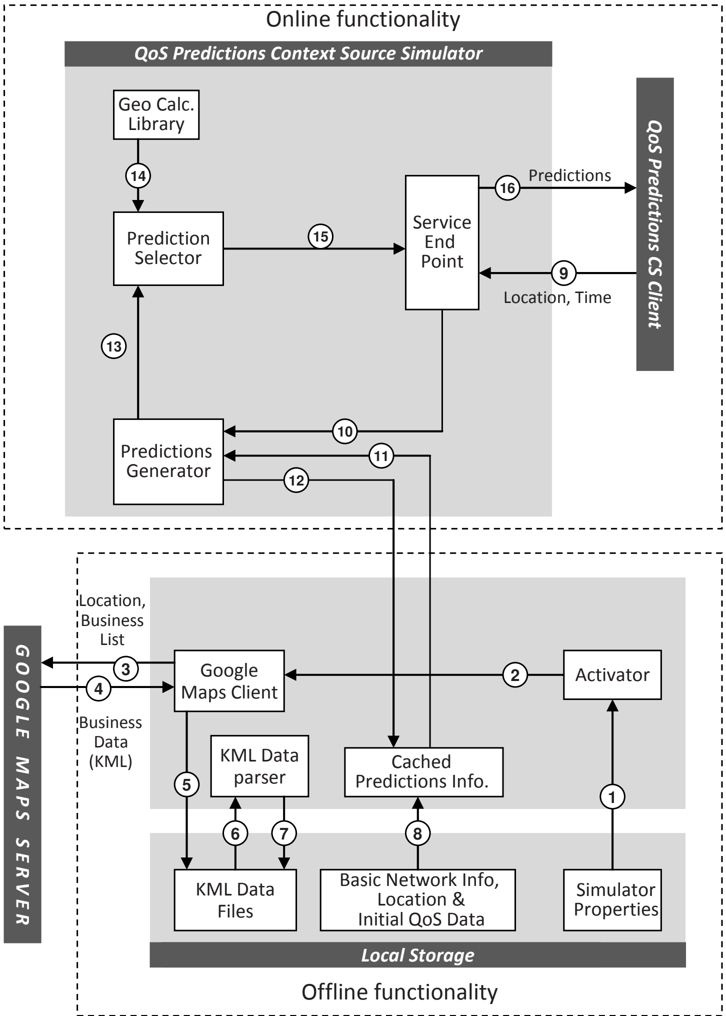


Figure 6.13: Components and interactions in the QoS Predictions CS Simulator

Components and Interactions in the QoSCS Simulator

The components of the QoSCS simulator and interactions between them are shown in Figure 6.13. The QoSCS simulator is implemented as a Jini service. In this simulator, the result of interactions labelled from 1 to 8 is used to generate QoS predictions in reply to the prediction request (interaction 9) from the client. To ensure that the QoS prediction requests are promptly satisfied, the interactions labelled from 1 to 8 are performed only once and the resulting predictions are cached locally in the simulator RAM. In contrast, the interactions labelled from 10 to 16 are performed online as a response to the QoS predictions requests. With reference to Figure 6.13, the offline functionality is performed once on the initialization of the QoS predictions CS service. This functionality is described as follows:

A. *The Activator* component reads simulator configuration properties (*step 1*) from the property file. These properties include *Jini lookup service host name* and *port*, *valid values of longitude* and *latitude*, *Google maps server address*, *list of businesses types* (e.g. `hotel, school, restaurant, market, hospital`) and *number of business of each business type* (`e.g. 100`) to be fetched from the Google maps server, *minimum* and *maximum goodput* as well as *delay* made available by the *WLAN* and *WWAN* networks, and *minimum* and *maximum range* of WLANs. A geographic location specified by a pair of longitude and latitude may represent coordinates of the city centre around which a number of business establishments can be observed.
B. The Activator initializes a *Google maps client* (*step 2*) and passes the relevant information so that the client sends request (*step 3*) to the Google maps server.
C. The Google maps server sends (*step 4*) a list of businesses including their names and location in the *Keyhole Markup Language* (KML) format to the client. The client writes this data to the KML data files in the local storage so that they could be retrieved later for parsing names and location information of the businesses (*step 5*).
D. The data in the KML files is read by the *KML Data Parser* to extract (*step 6*) names and locations of the businesses. This data combined with the goodput, RTT and range values read from the property file is used to generate WLAN base stations data such as their goodput and RTT characteristics (within the minimum and maximum value limits), ranges and authentication information. This data is written to the local storage (*step 7*) so that every time the simulator starts, it does not need to contact the Google maps server. The data generated in this step consists of QoS predictions along the location dimension, which are cached in the simulator (*step 8*).

The request for QoS predictions originating from the QoSCS client is received by the simulator (*step 9*) at the *Service End Point*. Later on in the simulator, the following events take place as part of an online functionality (see Figure 6.13). These events are described as follows:

E. The request for QoS predictions is forwarded to the Predictions Generator module which generates and adds prediction information (step 10) in time dimension to the cached predictions (step 11). The predictions generator module is responsible for assigning QoS values to a wireless network in the predictions. To model QoS fluctuations along the time dimension, the QoS generator randomly increases or decreases (up to 10%) the goodput and RTT values (still within minimum and maximum values) in a certain time slot. The duration of this time slot is random[25].

F. The cached predictions are always updated (step 12) to remember previously assigned QoS values, so that when the next prediction request is received, appropriate fluctuations can be added to the previous QoS characteristics. This data is then sent to the Predictions Selector (step 13).
G. The Predictions Selector uses a Geographic Calculation Library (available at http://www.zipcodeworld.com) to calculate the distance between a pair of coordinates (step 14) and to select closest networks to the current location of mobile device. The prediction selector calculates the prediction range and sends it (step 15) to the Service End Point. These QoS predictions are then relayed to the QoSCS client.

6.5.2 User Trip Simulator

To model user movements, researchers have used a number of user mobility models (e.g. [Bett01]). However, these models do not necessarily represent the real world situation. E.g., a model for the vehicular environment proposed in [ETSI98] is a random mobility model without any street structure. In this model, cars move with constant speed (v=120 km/h) and car change their direction every 20 m (with a probability of 20%). Only direction changes of up to +45° are possible. These kinds of movements do not occur in the real world, e.g. a direction change of 90° is certainly possible. To model geographic movements as close to the real world situation, similar to the approach used by the QoSCS simulator, the user trip simulator uses the source-destination route information available in the Internet (in our case, *Google maps server*). Figure 6.14 shows a sample request to obtain the route information and received list of coordinates representing a route.

[25] In Section 8.3.1 on the future work, we propose to analyze historic wireless network QoS data collected by QoS Information System [Wac09b] to analyze the relationship between spatiotemporal context information and wireless network QoS. The results of this study can be used in the predictions generator for assigning more realistic QoS values in time dimension.

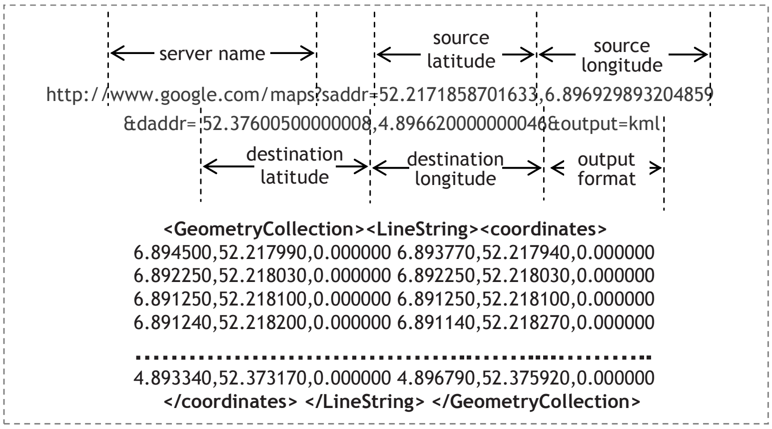


Figure 6.14: Sample HTTP request to obtain a list of coordinates representing a route between source and destination coordinates

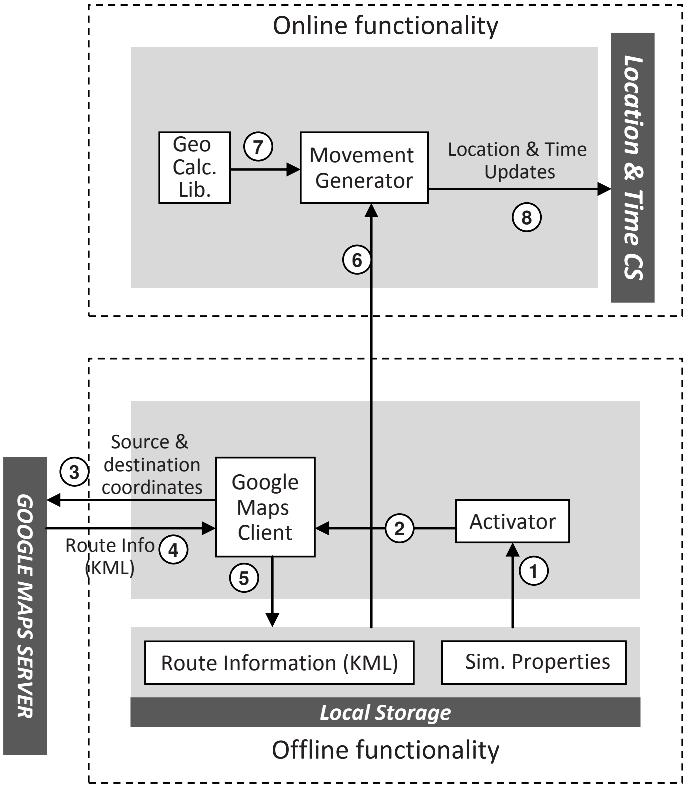


Figure 6.15: Components and interactions in the user trip simulator

Components and Interactions in the User Trip Simulator

The components of the *User Trip Simulator* and interactions between them are shown in Figure 6.15. To ensure that the location and time updates are promptly sent to the *location and time CS*, the interactions labelled from 1 to 5 are performed only once and resulting route information is cached locally in the simulator RAM. In contrast, the interactions labelled from 7 and 8 are performed online as a response to the initialization of *location and time CS*. Similar to the QoSCS simulator, the User Trip Simulator reads a user trip configuration *(step 1)* in terms of *source and destination coordinates*, *user speed* and initiates a Google Maps client *(step 2)* with this information to request geographic route information *(step 3)* from the Google maps server. The received route information *(step 4)* consists of a *sequence of steps* where each step has its own source and destination coordinates. Since no intermediate coordinates within a step are available, we assume that the user moves in a straight line between the source and destination coordinates of every step.

The route information is stored in a local storage *(step 5)* to avoid unnecessary requests to the Google maps server. A movement generator reads this information from the local storage *(step 6)* and uses a *Geographic Calculation Library (step 7)* to calculate the *constant bearing* between the source and destination coordinates represented by the corresponding step. In the land navigation terms, a bearing is an angle between a line connecting two points and a north-south line, or *meridian*. A *meridian* (or *line of longitude*) is an imaginary arc on the Earth's surface from the *North Pole* to the *South Pole* that connects all locations running along it with a given longitude. Once this bearing is obtained, it is easy to calculate intermediate location coordinates based on the values of obtained bearing and user speed. Similar to a GPS receiver, the movement generator updates simulation time and location changes *(step 8)* every second to the location and time context source.

6.5.3 Simulation Parameters and Experiment Runs

In this section, we describe simulation parameters and experiment runs to evaluate performances of the NAHO mechanism, the MCHO mechanism and the WWAN only mechanism.

Description of the Experiments

For the comparison between the MCHO mechanism and NAHO mechanism, the simulation environment includes two types of wireless networks namely WiFi (WLAN) and GPRS (WWAN). To take into account as many possible numbers of business places and institutes, the QoSCS simulator obtains a list of around 2000 such places from the Google maps server around *Geneva* (Switzerland) city centre. Since the initial experiments for QoS predictions in [Wac09b] are conducted in Geneva, for simulating the user mobility, a user trip originates at *Carouge* and ends at *Vernier* (both are municipalities in the Canton of Geneva) via the Geneva city centre.

This route shown in Figure 6.16 covers a distance of 8.470 km and the corresponding route obtained from the Google maps server consists of 107 steps.

To take into account the effect of speed on the number of handovers and network performance, the considered user speeds are 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 90 and 100 km/h. The biosignals profile used in these experiments is the cardio biosignals profile described in Section 5.4.1. Accordingly, the biosignals delivery goodput and RTT requirements are *25580 bps* and *500 msec* respectively [Pawa07b]. As a reasonable assumption, GPRS networks are available wherever the user goes. The AHP algorithm described in Section 6.3.2 assigns equal weight (0.50) to the goodput objective and delay objective. For the experimental comparison, along with the simulations of MCHO mechanism and NAHO mechanism, we also conducted simulations where the MBU uses only GPRS (WWAN) network. The WWAN network simulations do not involve any handover scenarios. Thus, in total we conducted 54 experiment runs – for 18 user speed levels and three approaches for biosignals transmission namely – WWAN only, MCHO mechanism and NAHO mechanism respectively. The data in Table 6.6 shows the duration of simulation run as a result of user speed. The simulation duration also includes 50 seconds of user inactivity time (i.e. the user is not moving) before the start of trip and 50 seconds inactivity time after the trip ends.

Table 6.6: Table showing the duration of simulation run according to the user speed

User Speed (in kmph)	*Duration of simulation run (in seconds)*	*User Speed (in kmph)*	*Duration of simulation run (in seconds)*
5	6209	50	712
10	3154	55	662
15	2137	60	610
20	1626	65	571
25	1321	70	536
30	1114	75	509
35	973	80	484
40	860	90	437
45	784	100	406

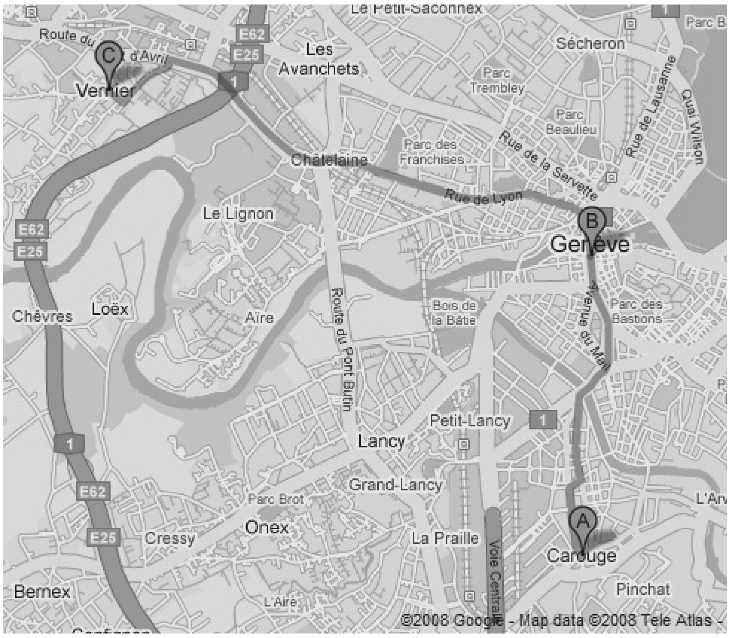


Figure 6.16: A map showing geographic route configured in the user trip simulator

6.6 Simulation Results

In this section, we present simulation results of experiments conducted according to the description in Section 6.5.3. The results presented in Section 6.6.1 depict comparative network performance of the mechanisms under consideration. The comparative vertical handover performance results of these approaches are presented in Section 6.6.2.

6.6.1 Network Performance Results

In this section, we present two sets of network performance result graphs. The first set of graphs shows an example of network performance result for a simulation run where the user speed is 40 kmph. The second set of results show the network performance results combined for all the 18 user speed levels.

Example of Network Performance Results for a Single Simulation Run

The first set of graphs shown in Figure 6.17, Figure 6.18 and Figure 6.19 show accumulated goodput, accumulated data loss and average RTT respectively for the user speed 40 kmph along the entire duration of one simulation run. In one simulation run, a user travels at a constant speed along the route A-B-C covering a distance of 8.47 kms as shown in Figure 6.16. The graphs shown in this section are representative of *general trends* observed for all the 18 user speed levels along the entire duration of user trip.

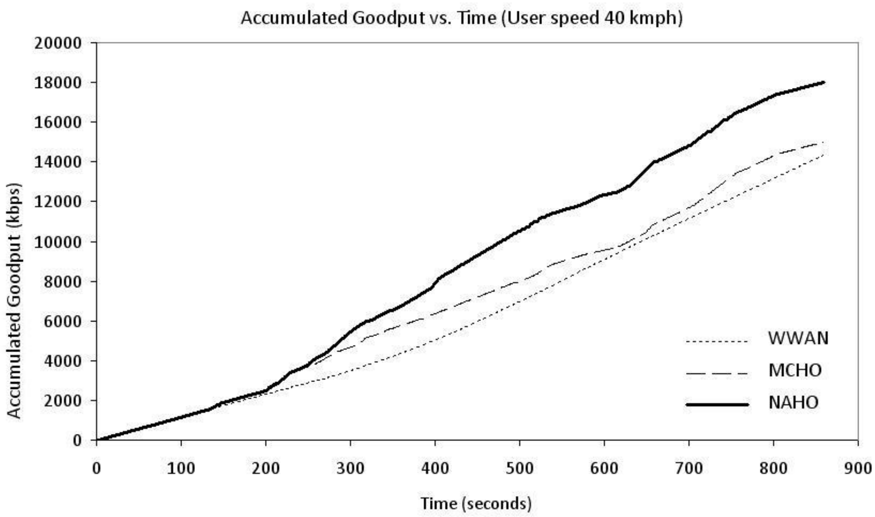


Figure 6.17: Comparison of accumulated goodput vs. time (40 km/h)

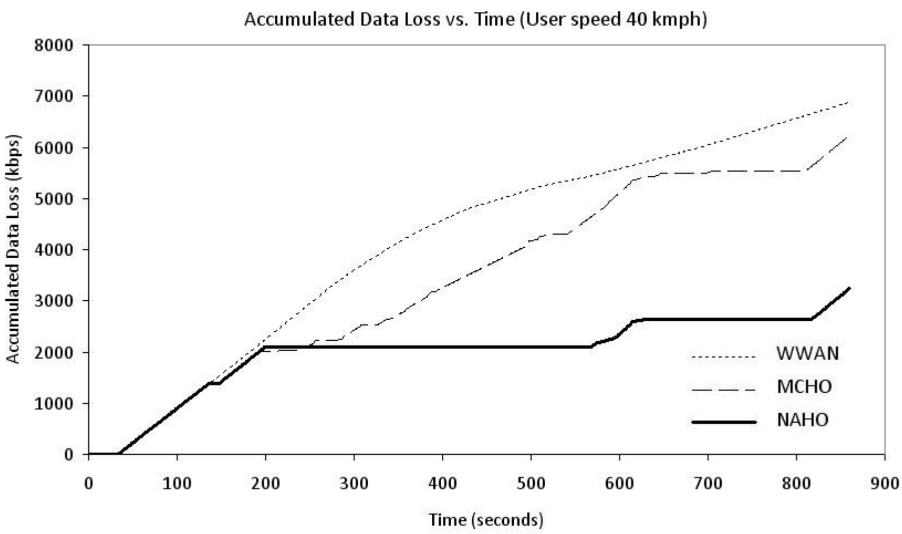


Figure 6.18: Comparison of accumulated data loss vs. time (40 km/h)

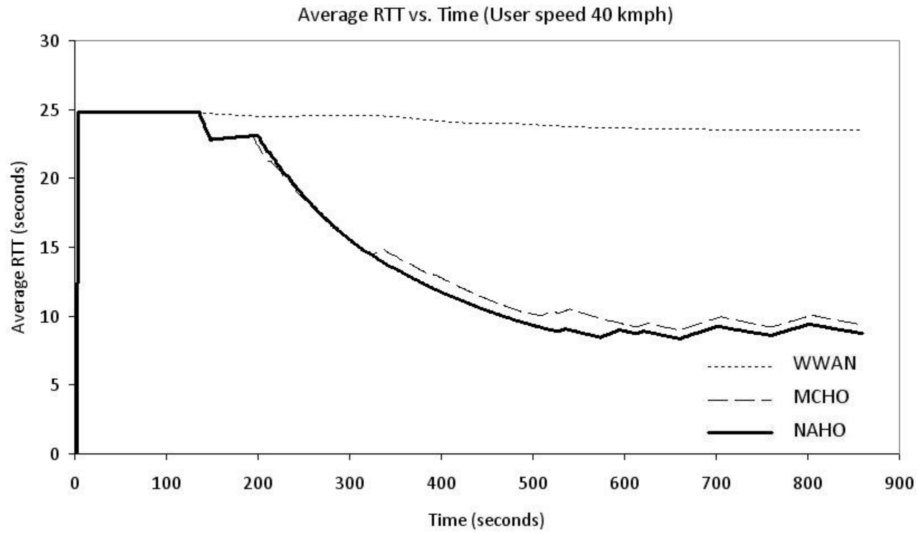


Figure 6.19: Comparison of average Keep-Alive RTT vs. time (40 km/h)

The statistics in Table 6.7 represents network performance statistics for a user speed of 40 kmph. It shows the average values of goodput, data loss and RTT for the three compared mechanisms. The statistics column named % *Difference* shows the difference between values obtained for a pair of approaches. E.g. A column titled *MCHO and WWAN* and row titled *Goodput (bps)* shows the performance of MCHO mechanism compared to the WWAN mechanism. For the network performance parameter goodput, a % difference with positive (negative) values shows an improvement (decline). For the parameters *data loss* and *RTT*, a % difference with negative (positive) values shows an improvement (decline).

Table 6.7: Statistics showing average values and % difference between the WWAN, NAHO and MCHO mechanisms for the user speed 40 kmph

Parameter	***Average Values***			***% Difference***		
	WWAN	*MCHO*	*NAHO*	*MCHO and WWAN*	*NAHO and WWAN*	*NAHO and MCHO*
Goodput (bps)	17100	17870	21440	4.5%	25.3%	20%
Data Loss (bps)	8190	7420	3850	-9.4%	-53%	-48%
RTT (milliseconds)	23550	9360	8740	-60.2%	-63%	-6.7%

Network Performance Results Continued

The second set of graphs shown in Figure 6.20, Figure 6.21, Figure 6.22 and Figure 6.23 show *average biosignal delivery goodput*, *average biosignal data loss*, *average keep-alive RTT* and *monitoring service's buffer fill level* respectively compared to the user speed levels. For the convenience of reader, these graphs represent relative performance difference between the values obtained for a pair of mechanisms which are: 1) *MCHO and WWAN*, 2) *NAHO and WWAN*, and 3) *NAHO and MCHO*, respectively.

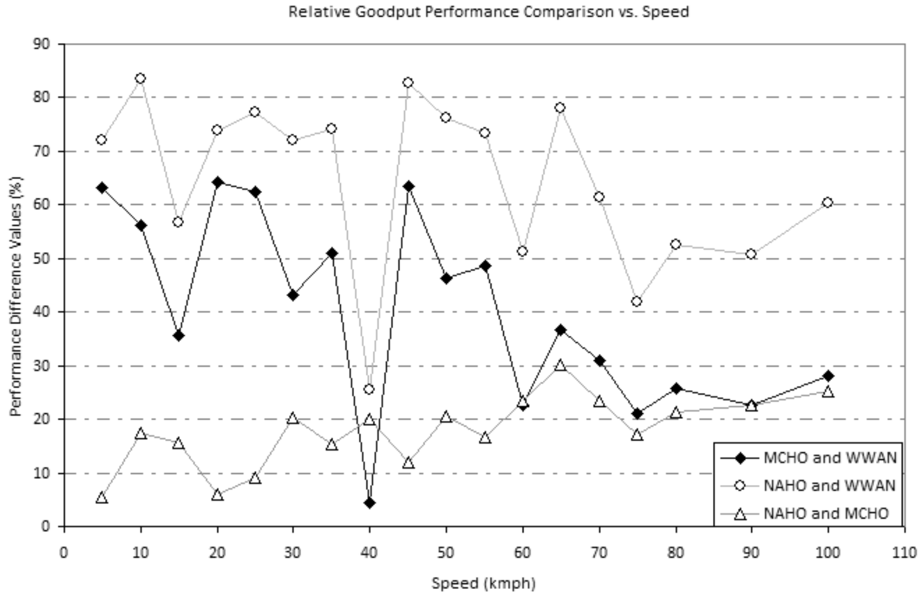


Figure 6.20: Relative goodput performance comparison vs. speed

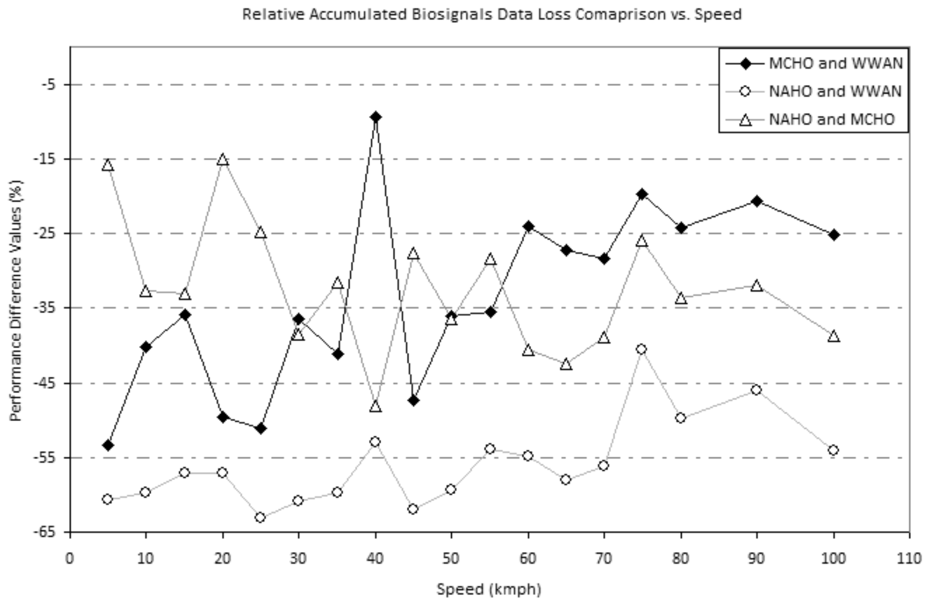


Figure 6.21: Relative accumulated biosignals data loss comparison vs. speed

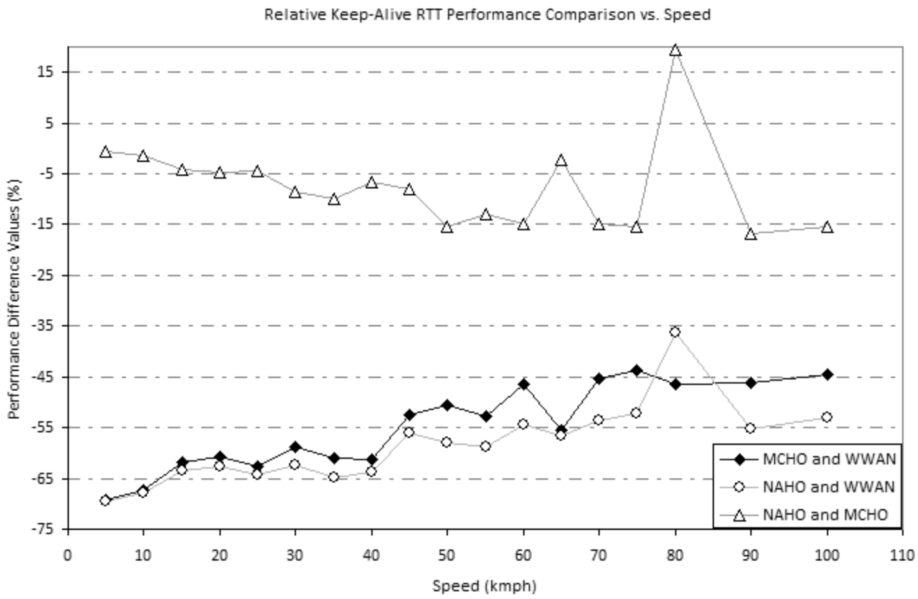


Figure 6.22: Relative keep-alive RTT performance comparison vs. speed

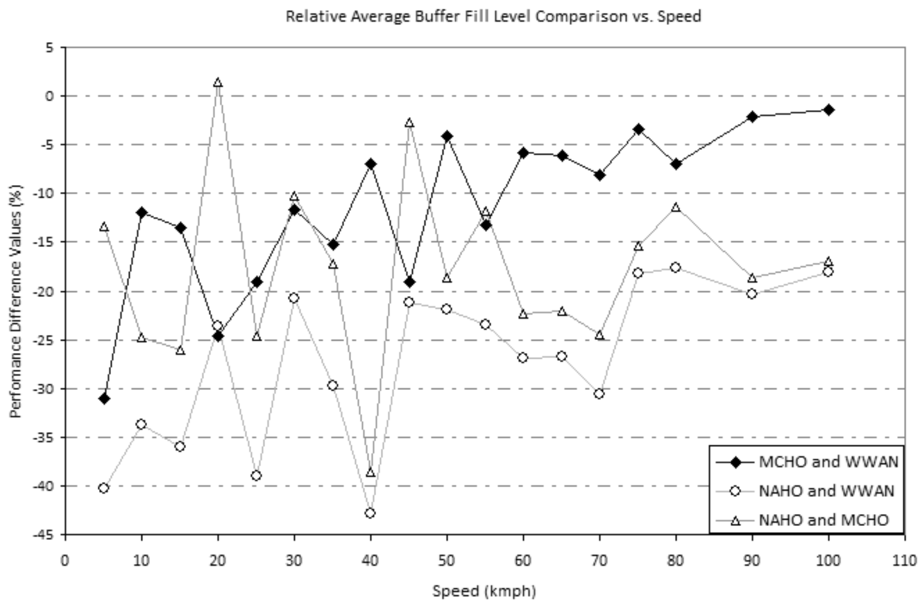


Figure 6.23: Relative average buffer fill level comparison vs. speed

The observed network performance trends from the results presented in this section are as follows:

1. Both of the proposed handover mechanisms - the MCHO mechanism and NAHO mechanism result in higher goodput, lower data loss and lower keep-alive RTT compared to the MHPMS that only uses WWAN for the biosignals delivery.
2. Among the two proposed mechanisms, for most of the simulation duration, the NAHO mechanism results in higher goodput, lower data loss and lower keep-alive RTT compared to the MHPMS that uses MCHO mechanism for the biosignals delivery.

However, in case of the keep-alive RTT, we encountered one instance at the user speed of 80 km/h where the NAHO mechanism provides 16 % higher keep-alive RTT compared to the MCHO mechanism. This behavior can be attributed to the multi-objective optimization nature of AHP. In this particular instance, NAHO mechanism provides 21 % higher goodput compared to the MCHO mechanism. Hence, it is possible that a wireless network which has a higher score for the goodput objective but lower score for the RTT objective may have been selected.

Summarizing these results and considering the exception discussed above, it can be concluded that in general as compared to the MCHO mechanism, the NAHO mechanism provides higher extra-BAN communication QoS for the biosignals delivery.

6.6.2 Vertical Handover Performance Results

The graphs in Figure 6.24 and Figure 6.25 depict *the total number of vertical handovers* and *disconnection time (in seconds)* respectively for the MCHO and NAHO mechanisms. The relative performance differences for these parameters between the NAHO mechanism and MCHO mechanism are shown as well. These parameters are not applicable for the WWAN mechanism, as there are no handovers involved in it.

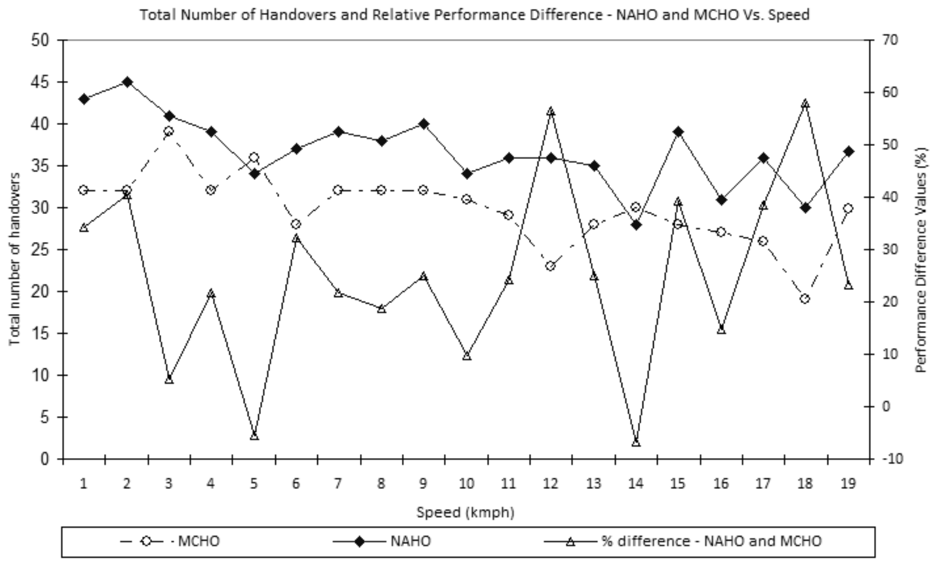


Figure 6.24: Total number of handovers and relative performance difference – NAHO and MCHO mechanisms vs. speed

Compared to the MCHO mechanism, we observe that the NAHO mechanism results in a higher number of handovers. This is due to the fact that once connected to the WLAN network, MCHO mechanism performs the handover only when the user is out of the coverage area of that WLAN network. In contrast, the NAHO mechanism may select another WLAN network as a result of context changes described in Section 6.3.1. Hence at any given time, there is a certain possibility of handover to another network though the user is in the coverage area of the network currently in use.

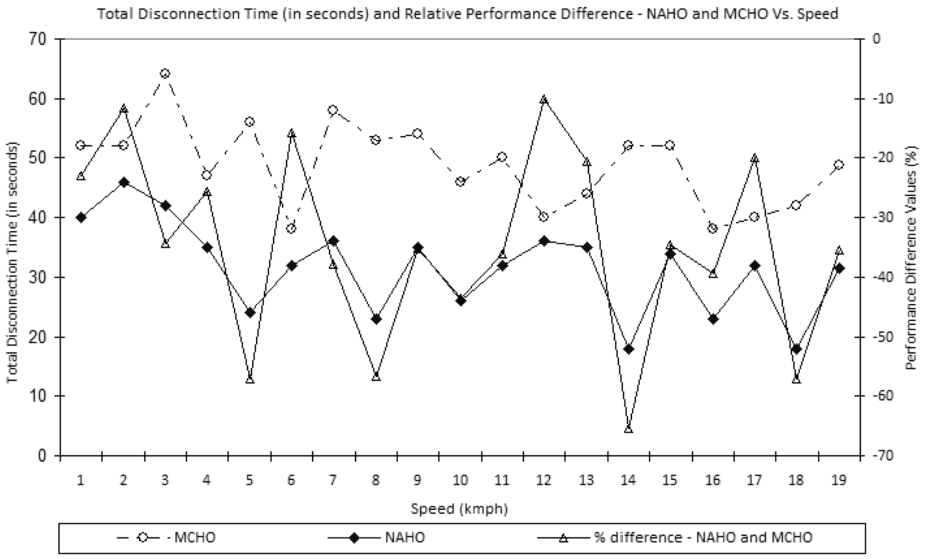


Figure 6.25: Total disconnection time (in seconds) and relative performance difference – NAHO and MCHO mechanisms vs. speed

Compared to the MCHO mechanism, the NAHO mechanism results in a lower amount of disconnection time. The disconnection occurs in the following cases: 1) The user moves out of the coverage area of a WLAN network; 2) During the handover execution phase. Since the MCHO mechanism results in a lower number of handovers, the reason for lower disconnection time of the NAHO mechanism is that the NAHO mechanism proactively handles the situation of users moving out of the WLAN network coverage area. This is feasible because the wireless network availability information is cached on the MBU in terms of QoS predictions and the location change events are periodically processed to determine *user on the wireless network boundary condition* (Section 6.3.1).

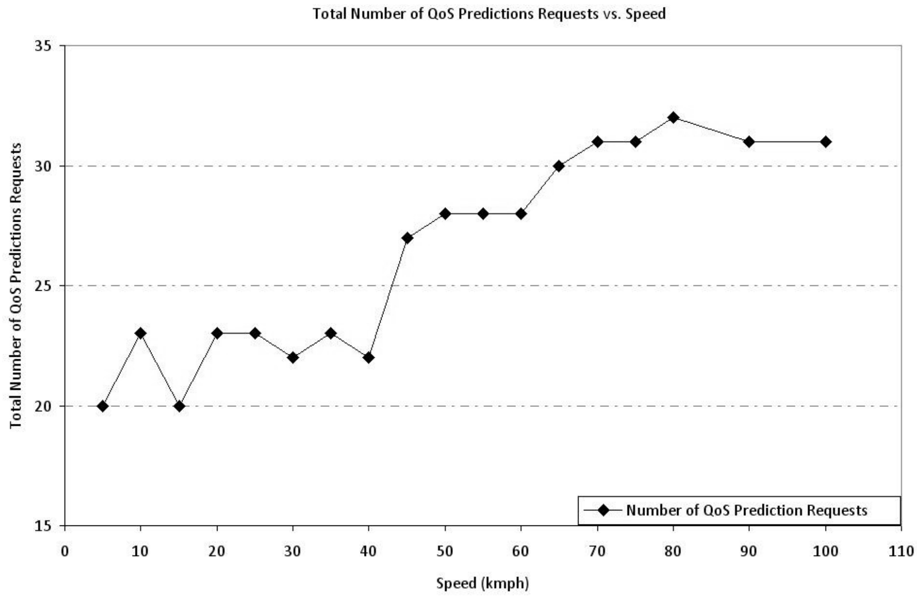


Figure 6.26: Total number of QoS prediction requests vs. speed

Figure 6.26 shows the *number of QoS prediction requests* originating from the MBU vs. *speed*. It is seen that the number of requests generally increases with the increase in user speed. This is also attributed to the provision of *user on the wireless network boundary condition* described earlier. At a higher speed, the user is likely to cross the wireless network boundary in a shorter amount of time. As a consequence, higher numbers of QoS prediction requests originate from the MBU.

6.6.3 Sample Statistics of the QoS Predictions Requests and Responses

One of the observed statistics about the working of the QoSCS simulator is shown in Table 6.8. This statistics is obtained during the simulation run (described in Section 6.5.3) when the user travels at a speed of 40kmph along the simulation path. In Table 6.8, the first column represents the number of QoS predictions request originating from the context processor. The second column shows the response time of QoSCS simulator after receiving a request from the QoS Predictions CS client (*step 9 in Figure 6.13*) and sending QoS predictions in a corresponding reply (*step 16 in Figure 6.13*). The third column, fourth column and fifth column in Table 6.8 show a composition of QoS predictions in terms of the *number of wireless networks*, *validity interval* and *location range*, respectively. The overhead of QoS predictions in terms of its data size is shown in the sixth column. On an average, the predictions size is 35426 bits (34.6 kb).

Table 6.8: Statistics about the QoS predictions requests and responses – for the user speed 40 kmph

Request No.	*Response Time (milliseconds)*	*Number of Wireless Networks*	*Validity Interval (minutes)*	*Location Range (meters)*	*Size of Predictions (bits)*
1	986	30	30	869	34008
2	772	30	30	509	36424
3	717	30	30	438	39320
4	741	30	30	356	35656
5	704	30	30	315	36424
6	701	30	30	225	35752
7	744	30	30	200	34992
8	714	30	30	260	34672
9	728	30	30	318	33968
10	759	30	30	240	33728
11	698	30	30	155	35104
12	726	30	30	138	35224
13	701	30	30	168	34960
14	764	30	30	126	34136
15	721	30	30	134	34784
16	721	30	30	162	34672
17	706	30	30	201	35752
18	704	30	30	273	35336
19	794	31	30	424	37352
20	735	30	30	545	35872
21	734	30	30	841	35120
22	679	30	30	1154	36112
Average	***738 seconds***	***30***	***30 minutes***	***365 meters***	***35425 bits***

6.7 Conclusions

The research reported in this chapter is conducted to address research objective 3 of this thesis. The resulting solution is named as *context-aware network assisted handover* (NAHO) mechanism. This mechanism takes a QoS-aware network selection decision by evaluating QoS requirements of continuous biosignals delivery against QoS offered by wireless networks surrounding the MBU. The proposed NAHO mechanism extends the mobile controlled handover (MCHO) mechanism in the following ways.

1) The NAHO mechanism proposes three context sources (CS) in addition to the communication CS which is used in the MCHO mechanism. The additional context sources are: *location and time CS* (on the MBU), *QoS requirements CS* (on the MBU) and *QoS predictions CS* (in the Internet). The information about MBU's present location and time is obtained from the location and time CS. The QoS requirements continuous biosignals delivery are provided by the QoS requirements CS. The context information about the availability of wireless networks and their application level QoS characteristics (goodput and RTT) as a function of location, time, wireless network provider and the network technology is provided by the QoS predictions CS hosted in the fixed network. This context information is known as *QoS predictions*.
2) The context processor component is responsible for collecting context information from all the context sources and prepares a *context snapshot* that represents QoS requirements of biosignals delivery and QoS offered by the wireless networks at the present location and time. The context processor consists of mechanisms to update the context snapshot on the context changes which are *location change*, *time change*, *QoS requirements change*, *new QoS predictions received* and *network unavailability*.
3) The network selection decision making in the NAHO mechanism is intended to select a wireless network that closely satisfies monitoring service's QoS requirements. To achieve this, the context processor uses an *Analytic Hierarchy Process* (AHP) based optimization algorithm which is a proven technique used for taking handover decisions in [Bala04, Ahme06]. The proposed AHP algorithm considers two optimization objectives: a) Satisfy monitoring service's goodput requirements; and b) Satisfy monitoring service's RTT requirements.

Since the QoS predictions research is currently in the exploratory stage, for the evaluation of the NAHO mechanism, we chose a simulation based approach. For this purpose, we designed hierarchical structure of QoS predictions and built two simulators namely *QoS Context Source Simulator* and *User Trip Simulator*. To be able to realistically represent locations of the WLAN base stations and user trip movements, both of these simulators use the geographic information available in the Internet (in our case *Google Maps Server*) for the modeling of WLAN locations and user movements respectively.

The proposed NAHO mechanism is evaluated using simulations to compare its performance with the MCHO mechanism (Chapter 5) and WWAN mechanism (the MBU uses only WWAN network (e.g. GPRS) for biosignals delivery.) The performance evaluation objectives are of the following two types: 1) network performance in terms of biosignal delivery goodput, keep-alive RTT, and biosignals data loss; 2) vertical handover performance in terms of the number of handovers, network disconnection time and number of QoS predictions requests.

The statistics shown in Table 6.9 represents average values of network performance parameters for all three compared mechanisms. The statistics column named *Relative Performance Difference* shows the difference between values obtained for a pair of mechanisms. E.g. A column titled *MCHO and WWAN* and row titled *Goodput (bps)* shows the goodput performance of MCHO mechanism compared to the WWAN mechanism.

Table 6.9: Statistics showing network performance in terms of average values and relative performance difference between the WWAN, NAHO and MCHO mechanisms

Parameter	**Average Values**			**% Difference**		
	WWAN	*MCHO*	*NAHO*	*MCHO and WWAN*	*NAHO and WWAN*	*NAHO and MCHO*
Goodput (bps)	11880	16510	19380	40.3 %	64.6 %	17.8 %
Data Loss (bps)	13330	8710	5840	-33.6 %	-56 %	-32.4 %
RTT (milliseconds)	20510	9130	8370	-54.8 %	-58.4 %	-7.6 %

Comparing these results with the QoS requirements, it is observed that the NAHO mechanism provides higher extra-BAN communication QoS to the monitoring service compared to the WWAN mechanism and MCHO mechanism. The WWAN only mechanism performs the worst while the performance of MCHO mechanism is better than the WWAN mechanism. The observed performance improvement of the NAHO mechanism is due to the availability of context sources providing QoS predictions and the AHP based decision making which performs network selection based on the importance of optimization objectives. In this case, it is confirmed that the NAHO mechanism results in a better network selection compared to the MCHO mechanism.

The statistics in Table 6.10 represents averaged vertical handover performance results. It shows the values network disconnection time and number of handovers for the MCHO and NAHO mechanism, respectively. The statistics column named *Relative Performance Difference* shows the comparative difference between the NAHO and MCHO mechanisms. This column shows that the NAHO mechanism results in a lower disconnection time and higher number of handovers compared to the MCHO mechanism. The reason behind higher number of handovers is frequent processing of context change events in the context processor. Asa result it is likely that the context reasoner invokes AHP network selection algorithm frequently. The reason behind lower disconnection time is that the NAHO mechanism proactively handles the situation of users moving out of the coverage area of WLAN network, thus eliminating the disconnection time resulting from the user movements.

Table 6.10: Statistics showing vertical handover performance and relative performance difference between the NAHO and MCHO mechanisms

Parameter	***Average Values***		***% Difference***
	MCHO	***NAHO***	***NAHO and MCHO***
Disconnection Time (seconds)	48	31	-35 %
Number of Handovers	29	36	23 %

The statistics in Table 6.11 show the overhead of QoS predictions for the NAHO mechanism. The context processor requests QoS predictions on an average 26 times per simulation run. The average response time of the QoS CS simulator is 692 milliseconds per prediction request. The predictions are requested in two cases – when the user moves outside the location range or on the expiry of validity interval.

Table 6.11: Statistics showing overhead of QoS predictions

Parameter	***Average Value***
Number of QoS Prediction Requests	26
Average Response Time	692 ***milliseconds***

In summary, we conclude that the NAHO mechanism – in particular the choice of context sources, design of context processor and context reasoner components together provision necessary mechanism to select a wireless network that closely satisfies QoS requirements of biosignals delivery during a mobile patient monitoring session. The obtained results also support the claim made in Section 5.1.4, that the use of QoS predictions may prove more beneficial for use in the MHPMS.

Chapter 7

NAHO Mechanism for Power Savings[26]

Research objective 4 of this thesis is the following: How to use the wireless network interfaces of the MBU to reduce its power consumption? Though the advanced mobile devices have increased memory and processing capabilities, the power consumption of communication interfaces during the patient monitoring session is a major issue. In this chapter, we propose two variants of the *network assisted handover* (NAHO) *mechanism* (Chapter 6) those make use of QoS predictions to switch off unused network interfaces of the MBU. We conducted simulations to compare the performance of NAHO variants with the NAHO mechanism. The experimental results in this chapter also address a part of research objective 5 namely analyzing the gains and corresponding overheads associated with the proposed NAHO mechanism for power savings.

This chapter is organized as follows: Section 7.1 introduces the problem and provides motivation behind the proposed NAHO variants. Section 7.2 explains detailed working of the proposed NAHO variants. Section 7.3 defines performance evaluation objectives to measure the power savings performance. Section 7.4 outlines simulation setup of the experiments. Section 7.5 discusses simulation experiment runs, obtained results and their interpretation. Section 7.6 concludes the chapter.

7.1 Introduction and Motivation

During the power consumption study of MHPMS conducted in [Wac09a], it is observed that a significant amount of power is consumed by the MBU network interfaces (NIs) for biosignals delivery. This is of concern for the mobile patient monitoring applications intended for the continuous patient monitoring purposes. E.g. The *wireless Continence Management System* [Wai08] is aimed at 24 hours monitoring of elderly dementia patients residing within the nursing home and suffering from incontinence. If the MHPMS is used for these types of healthcare

[26] This chapter is based on our work published in [Pawa08a], [Pawa08c], [Pawa09a], [Pawa09b] and [Wac09a].

applications, the MBU needs to be power efficient to be able to deliver patient's biosignals for a longer duration of time. In another example, it may be necessary for the MHPMS trauma patient monitoring case (Section 4.1.3) to continuously deliver patient's biosignals to the back-end system for longer duration of time than anticipated (e.g. road traffic outage). The battery of a patient's MBU device (e.g. QTEK9090) typically lasts for few hours in a continuous mobile patient monitoring session [Halt04, Wac09a], whereas 24 hours battery life is expected in such scenarios [Kuma08]. The MBU used in the MHPMS consists of two network interfaces (WWAN and WLAN) for the wireless Internet connectivity. At a given time, only one NI can be used for delivering biosignals data i.e. in the ON-ACTIVE state. The other unused NI is usually in the ON-IDLE state – to discover wireless networks in the patient's mobility path. It is to be noted that the amount of power consumed by the NI in the ON-ACTIVE state is dependent on the amount of data to be transferred [Wac09a] and distance of a mobile device from the wireless base station.

In the literature survey of vertical handover approaches presented in Chapter 3, an application oriented vertical handover approach in [Chen05] features an entity named as the *Location Service Server* (LSS). The LSS is intended to provide wireless network information such as coverage area, bandwidth and latency to the mobile devices via network base stations. The QoS Information System (QoSIS) providing QoS predictions is an entity similar to the LSS. However, no specifications are provided in [Chen05] about how LSS obtains the QoS information of a particular wireless network. The LSS and QoSIS differ in this aspect. In [Chen05], the wireless network availability and QoS information obtained from the LSS is utilized to selectively turn off the wireless NI to achieve power savings on the mobile device. The wireless NI activation strategies in [Chen05] are the following: 1) *always on*, 2) *periodically on* and 3) an *active application oriented* (AAO) handover. In the always on activation strategy, the WLAN NI is activated all the time. In the periodically on strategy the WLAN NI is activated for 500ms in every 3 seconds. In the AAO scheme the WLAN NI is activated when the mobile device needs higher bandwidth for data-intensive applications. The simulation results of these NI activation strategies showed that using the AAO strategy, the power consumption of a mobile device can be reduced.

We think that the QoS predictions can be used in a way similar to that of the active application oriented handover [Chen05] to achieve power savings on the MBU. Hence, herewith, we propose and evaluate two variants of the NAHO mechanism which selectively turn off the unused NI on the MBU. The first proposed NAHO variant is the $\text{NAHO}_{\text{WLAN-OFF}}$ in which the WLAN NI is switched off when not in use. The second proposed NAHO variant is the $\text{NAHO}_{\text{WLAN-OFF,WWAN-OFF}}$ in which either of the WWAN or WLAN NI is switched off based on the current NI in use for the biosignals delivery.

The experiments to determine power consumption characteristics of the wireless NIs are widely reported in the literature. The results of these experiments are typically used for energy-aware application design. E.g. the experiments to obtain energy consumption measurements of the IEEE 802.11 NI are reported in [Feen11].

In these experiments, the values of energy consumption were obtained by direct measurement of an input voltage and current draw at the network device. The other way to obtain power consumption values is by using operating system functions to obtain the current energy level of a mobile device. E.g. the experiments to determine NI power consumption of two PDAs - QTEK 9090 and IPAQ reported in [Barg07] use *GetSystemPowerStatusEx* function of the Microsoft Windows Mobile OS. This way the NI power consumption values can be determined in practice. Continuing with the use of context-aware computing based architecture, we consider that the power consumption related data of the MBU is another type of context information. Hence we introduce one more context source named as *power context source* (power CS) which provides context information about the power consumption of MBU NIs. The unit of NI power consumption considered herewith is *watt*. However, the energy stored in the MBU battery is counted in *Joules*. If the NI power consumption value and the current energy level of the MBU battery are known, it is possible to estimate the duration of biosignals delivery till the point in time the MBU battery is out of power. This estimated duration is helpful to make a choice of NI (and the wireless network to which a MBU connects using the selected NI) during the handover decision making process. In the proposed NAHO variants, the context information obtained from the power CS is used by the *analytic hierarchy process* (AHP) based context reasoner as additional information for taking a power-aware network selection decision. The information about power CS and proposed NAHO variants is illustrated in Section 7.2.

The simulation experiments in this chapter are aimed at comparing power savings performance of the NAHO variants proposed herewith with the NAHO mechanism proposed in Chapter 6. In order to evaluate power savings aspects of the proposed NAHO variants, herewith we use the NI power consumption values of two mobile devices. The first mobile device is a QTEK 9090 PDA and the second mobile device is an IPAQ PDA. The NI power consumption study of these handheld mobile devices during the transfer of streaming data is conducted in [Wac09a] and [Barg07].

7.2 Proposed NAHO Mechanism Variants for Power Savings

The architecture of proposed NAHO mechanism that interacts with the power CS is shown in Figure 7.1. This architecture extends the NAHO mechanism architecture in Chapter 6 in the following ways:

- Addition of the power CS;
- The two proposed variants of NAHO mechanism are: NAHO, $\text{NAHO}_{\text{WLAN-OFF}}$ and $\text{NAHO}_{\text{WLAN-OFF,WWAN-OFF}}$;
- The context snapshot described in Section 6.3.1 is extended to accommodate context information obtained from the power CS; and
- The AHP process of NAHO mechanism considers one additional objective namely the *power savings objective*.

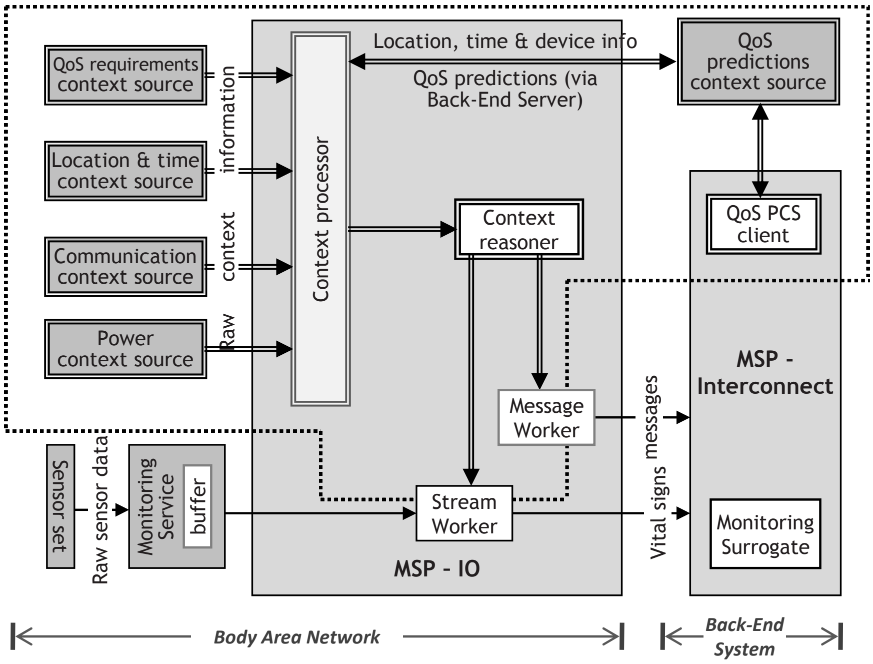


Figure 7.1: Architecture of NAHO mechanism that interacts with the power context source

7.2.1 Power Context Source

In line with commercially available handheld mobile devices, we consider that the MBU is equipped with one *Wireless Wide Area Network* (WWAN) interface (e.g. GPRS and/or UMTS) and one *Wireless Local Area Network* (WLAN) interface (e.g. WiFi).

States of the network interfaces

From the data transfer perspective, at any given time, the network interface (NI) of the MBU is in one of the following states:

- *OFF*: No IP connectivity.
- *POWERING-ON:* This is an intermediate state required to switch on the NI.
- *ON-IDLE*: an *IP-idle* state, where the NI has IP connectivity to the Internet. However it does not send/receive any IP packets carrying application-data.
- *ON-ACTIVE*: an IP-active state, where the MBU is sending or receiving application level IP packets through this NI.

Combining the states of two NIs (WLAN and WWAN each), there exist in total 16 different states. Theoretically, to determine power consumption for each of the NI state combinations, power consumption values of individual NI in each state (i.e. in total 8 values for 2 NIs) are required, so that 16 different states follow from some mathematical formula. However, this was not the case observed in practice from the experiments conducted in [Barg07, Wac09a]. Therein it was possible to obtain power consumption values of 8 different NI state combinations (See Table 7.1).

Table 7.1: Possible network interface state combinations

NI State Combinations	
GPRS (WWAN)	**802.11b (WLAN)**
OFF	OFF
OFF	ON-IDLE
OFF	ON-ACTIVE
ON-IDLE	OFF
ON-IDLE	ON-IDLE
ON-IDLE	ON-ACTIVE
ON-ACTIVE	OFF
ON-ACTIVE	ON-IDLE

Context information

To make use of QoS predictions for power savings, we propose that the power CS provides two types of context information: namely *static context information* and *dynamic context information*. As the name indicates, the values of static context information do not change, while the values of dynamic context information change continuously at a certain interval[27]. A brief description of the context information provided by power CS and its intended use is presented in Table 7.2.

Static context information: The static context information provided by the power CS includes the following:

1. *The power consumption values* (in Watt) *of a particular NI state combination* shown in Table 7.1. The NI power consumption values during the *POWERING-ON* state is also necessary, since the POWERING-ON is an intermediate state required to switch on the NI;
2. *Maximum battery capacity*: (in Joules) of the MBU as determined from the specifications of the MBU battery; and
3. *Power savings preference value*: This parameter is introduced to assist in the AHP decision making. The value of this parameter represents how important is the power savings objective compared to the goodput objective and the RTT objective. In the current setting, the power savings preference may take any of the integer values in the range 1–5 (from the least important to the most important compared to goodput objective

[27] Since the NI power consumption values per second are available, this duration is configured to 1 second for the experiments.

and RTT objective). The idea of assigning this range is motivated from the BenQ handover management approach [Ahme06] surveyed in Chapter 3. In the approach proposed in [Ahme06], the user preferences are modeled as user-friendly options labeled with suitable *literals* which a user arranges in certain order of priority.

Dynamic context information: Dynamic context information provided by the power CS is the *remaining battery power of the MBU* (in %). This value is used by the context reasoner to calculate the value of a parameter named *estimated battery depletion time* for each of the NI state combinations. The estimated battery depletion time refers to an estimated duration of a patient monitoring session if a particular NI state combination is used for the transfer of biosignals.

Table 7.2: Brief description of the context information provided by the power context source

Context Information	***Intended Use***
1. Maximum battery capacity of the MBU 2. Remaining battery power of the MBU (in %) 3. Power consumption in Watt for a combination of NI states 4. NI power consumption during the POWERING-ON state. 5. Value of the power savings preference in a range of 1–5 (from the least important to the most important)	• The maximum battery capacity, remaining battery power and power consumption values of NI states are used by the context reasoner during AHP calculation to assign score to the wireless network. • The value of power savings preference is useful to decide the weights of AHP optimization objectives in the Context Reasoner.

7.2.2 NAHO mechanism variants for the power savings objective

Herewith we present two variants of the NAHO mechanism for the power savings objective. The rationale behind proposing these two variants is as follows: Due to the availability of QoS predictions on the MBU, the wireless network availability is known as well. Because of this reason, it is not required to keep the NI powered on specially to search for the network availability. Hence, the NI which is not transmitting biosignals can be selectively turned off. Provided this argument, the proposed NAHO mechanism variants are described in the following and summarized in Table 7.3:

- ***NAHO:*** This is an original NAHO mechanism in which both the NIs of the MBU are always powered on (no NI is in the OFF state). As a result, if the WWAN NI is in use (i.e. ON-ACTIVE state) for biosignals transfer then the WLAN NI is in an ON-IDLE state and vice versa.
- ***NAHO$_{WLAN\text{-}OFF}$:*** This is the NAHO variant in which the WWAN (GPRS) NI is always powered on. However, if the WLAN (WiFi) NI is not in use for the biosignals transfer, then it is powered off. This strategy is motivated from the fact that the WWAN connectivity is ubiquitous, hence in case where a WLAN

suddenly becomes unavailable or the WLAN is not available, it is easy to switch to WWAN immediately without waiting for NI activation. If the WWAN network is selected for the handover, then the WLAN NI is switched off. If the WLAN network is selected for the handover, the WLAN NI is switched on if it is in the *OFF* state.

- ***NAHO$_{WLAN\text{-}OFF,WWAN\text{-}OFF}$*:** This variant is an extension of the NAHO$_{WLAN\text{-}OFF}$ variant. This variant is introduced to study the effect of switching off a WWAN interface on the power savings. If the WWAN (WLAN) network is selected for the biosignals delivery, then the WLAN (WWAN) NI is switched off.

Table 7.3: NAHO mechanism variants and NI state combinations based on the type of wireless network in use

NAHO variant	*WWAN network in use*	*WLAN network in use*
NAHO	[WWAN ON-ACTIVE, WLAN ON-IDLE]	[WWAN ON-IDLE, WLAN ON-ACTIVE]
NAHO$_{WLAN\text{-}OFF}$	[WWAN ON-ACTIVE, WLAN OFF]	[WWAN ON-IDLE, WLAN ON-ACTIVE]
NAHO$_{WLAN\text{-}OFF,WWAN\text{-}OFF}$	[WWAN ON-ACTIVE, WLAN OFF]	[WWAN-OFF, WLAN ON-ACTIVE]

7.2.3 Context processor and context reasoner components

The task of a *Context Processor* (CP) component is to *get/subscribe* context information from the context sources to generate a *context snapshot* and provide this context snapshot to the context reasoner for making a network selection decision at a given location and time. Compared to the context snapshot described in Section 6.3.1, the *context snapshot* for power savings application additionally includes information obtained from the power CS. This context snapshot is shown in Figure 7.2.

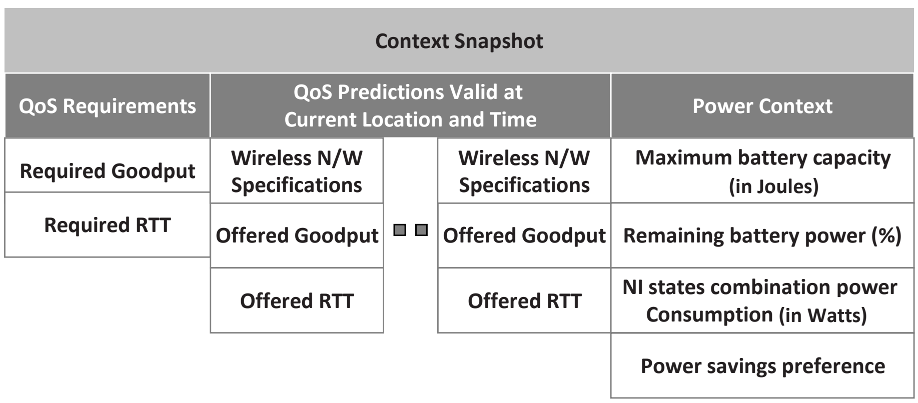


Figure 7.2: A structure of context snapshot showing context information obtained from the power CS

Since the value of parameter *remaining battery power (%)* of the MBU changes with time, the CP processes this context change event as follows:

Change in the remaining battery power: In this case a new context snapshot is created which reflects the latest value of the remaining battery power (%).

The other context change events processed by CP are same as described in Section 6.3.1.

AHP algorithm that includes the power savings objective

Herewith, we extend the AHP algorithm proposed in Section 6.3.2 to evaluate a candidate wireless network based on the amount of power required by the corresponding MBU network interface. Based on the NI power consumption value and remaining energy level of the MBU battery, the *expected battery depletion time* till the point in time the MBU battery is out of power can be calculated. This estimated duration is helpful to make a choice of a wireless network the selection of which will result in minimum power consumption of the MBU. Based on the information received from the current context snapshot, the context reasoner (CR) applies an *Analytic Hierarchy Process* (AHP) [Saat90] based algorithm to satisfy the following optimization objectives:

1) *Goodput objective:* Satisfy monitoring service's goodput requirements;
2) *RTT objective:* Satisfy monitoring service's RTT requirements; and
3) *Power savings objective:* Minimize power consumption of the MBU.

Herewith we assume that the goodput objective and the RTT objective are equally important. In comparison, the importance of the power savings objective is determined based on the power savings preference value. To calculate objective weights, firstly, it is required to normalize objective values. Hence, we map the value of power savings preference (one of the following: 1, 2, 3, 4, 5) to the normalized value of power savings objective (one of the following respectively: 0, 25, 50, 75, 100). This is denoted as $VALUE_{Power}$. Since the value of power savings preference represents how important is the power savings objective compared to the QoS objectives, the normalized value of goodput objective and RTT objective is calculated as ($100 - VALUE_{Power}$), each.

Working of the AHP algorithm

The CR applies following AHP steps to take a network selection decision when applied to the power savings objective:

Step 1: *Decide the weights of goodput, RTT and power savings objectives based on the value of a power savings preference*. The combined sum of AHP objective weights is always 1. This is a following sub-step process:

a) $VALUE_{Goodput} = VALUE_{RTT} = 100 - VALUE_{Power}$
b) $WEIGHT_{Goodput} = VALUE_{Goodput}/(VALUE_{Goodput} + VALUE_{RTT} + VALUE_{Power})$
c) $WEIGHT_{RTT} = VALUE_{RTT}/(VALUE_{Goodput} + VALUE_{RTT} + VALUE_{Power})$
d) $WEIGHT_{Power} = VALUE_{Power}/(VALUE_{Goodput} + VALUE_{RTT} + VALUE_{Power})$

The information in Table 7.4 shows the weights of three AHP objectives calculated according to the above steps for all the values of power savings preferences.

Table 7.4: AHP optimization objective weights for all the values of power savings preference

Power savings preference	VALUE Power	VALUE Goodput	VALUE RTT	WEIGHT Goodput	WEIGHT RTT	WEIGHT Power
1	0	100	100	0.5	0.5	0
2	25	75	75	0.43	0.43	0.14
3	50	50	50	0.333	0.333	0.333
4	75	25	25	0.2	0.2	0.6
5	100	0	0	0	0	1

Table 7.5: NAHO mechanism variant and estimated battery depletion times. For the computation, we refer to NI state combination power consumption values shown in Table 7.7 for the IPAQ device

NAHO variant	WWAN network available – N1	Estimated battery depletion time for N1 (in minutes)	WLAN network available – N2	Estimated battery depletion time for N2 (in minutes)
NAHO	[WWAN ON-ACTIVE, WLAN ON-IDLE]	145	[WWAN ON-IDLE, WLAN ON-ACTIVE]	159
$NAHO_{WLAN\text{-}OFF}$	[WWAN ON-ACTIVE, WLAN OFF]	151	[WWAN ON-IDLE, WLAN ON-ACTIVE]	159
$NAHO_{WLAN\text{-}OFF,WWAN\text{-}OFF}$	[WWAN ON-ACTIVE, WLAN OFF]	151	[WWAN-OFF, WLAN ON-ACTIVE]	164

E.g. If the value of power savings preference is 4, then the $VALUE_{Power}$ is 75. The following calculations take place to determine objective weights:

$VALUE_{Power} = 75$

$VALUE_{Goodput} = VALUE_{RTT} = 100 - 75 = 25$

$WEIGHT_{Goodput} = 25/(25 + 25 + 75) = 0.2$

$WEIGHT_{RTT} = 25/(25 + 25 + 75) = 0.2$

$WEIGHT_{Power} = 75/(25 + 25 + 75) = 0.6$

At the end of this step, for the power objective, depending on the type of NAHO variant (i.e. either of the NAHO, $NAHO_{WLAN\text{-}OFF}$, or $NAHO_{WLAN\text{-}OFF,WWAN\text{-}OFF}$) expected battery depletion time for each type of network is calculated.

E.g. consider the situation where MBU device is QTEK 9090, its battery is fully charged (storing 19847 Joules, remaining battery power is 100%) and two networks N1 and N2 are available at a particular location and time. The first network N1 is GPRS network (WWAN) and the second network N2 is 802.11b network (WLAN).

In this situation, the expected battery depletion times for the candidate N1 network and candidate N2 network are shown in Table 7.5.

Step 2: *Compute relative weight of each available network for each of the objectives:* This step consists of the following sub-steps:

a). For each of the three objectives, assign a score on the scale from 1 to 9 to each pair of available networks for creating a *pair-wise comparison matrix* P_{ij}. For a *network pair (N1, N2)*, a value 1 means that the network *N1* is *equally important* to network *N2*. The score of value 5 (9) means that the network *N1* is *strongly (absolutely) more important* than network *N2*. The s*core (N2, N1)* is an inverse of the *score (N1, N2)*.

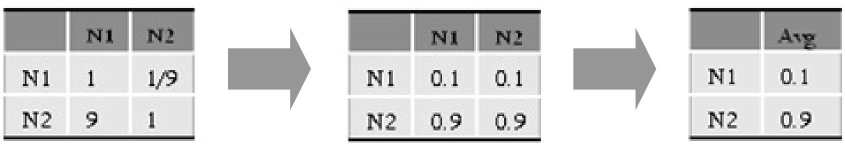
For the goodput and RTT objectives, we assign these values to the pair of network depending on how well *each network satisfies goodput and RTT requirements* of the biosignals delivery. This value assignment is same as described in Section 6.3.2. For the power objective, we assign these values corresponding to the difference between expected battery depletion times for the respective network types. E.g. continuing the example illustrated in Step 1, the scores assigned to the network N1 and network N2 are shown in Table 7.6.

Table 7.6: Calculation of network scores for two networks N1 and N2. For the computation, we refer to NI state power consumption values shown in Table 7.7 for the IPAQ device

NAHO variant	*Estimated battery depletion time for N1 (in minutes)*	*Estimated battery depletion time for N2 (in minutes)*	*Difference*	*AHP scores*
NAHO	145.75	159.54	N2 > N1, 13.79	N1 = 1/9, N2 = 9
NAHO$_{WLAN\text{-}OFF}$	151.90	159.54	N2 > N1, 7.64	N1 = 1/9, N2 = 9
NAHO$_{WLAN\text{-}OFF,WWAN\text{-}OFF}$	151.90	164.14	N2 > N1, 12.24	N1 = 1/9, N2 = 9

b). For each of the optimization objective, normalize each P_{ij} (divide by the sums of the columns) and average across rows to obtain the relative weights of the networks W_{no}.

E.g. considering two networks N1 and N2 for the NAHO$_{WLAN\text{-}OFF}$ variant, a *pair-wise comparison matrix, normalized weight matrix* and *network weights* for the power savings objective is shown in Figure 7.3.



(a) Pair-wise Comparison Matrix **(b) Normalized Matrix** **(c) Network Weights**

Figure 7.3: AHP calculation example for the power savings objective

Step 3: *Calculate the overall score for each network and select the network having the highest score:* The overall network score is the sum of relative network weights multiplied by the objective weight. The most optimal network is the network with the highest overall score.

In the example shown in Figure 7.3, the network N2 has higher score compared to network N1 for the power objective because it results in higher estimated battery depletion time. If the value of a power savings preference is 5 (power savings objective is the most important), the network chosen for handover is network N2.

7.3 Simulation Based Performance Evaluation Parameters

The goodput and delay optimization objectives are related to the QoS performance of a candidate network. Hence, in this section, we include performance evaluation parameters to measure the network performance. To measure the performance of power savings objective, we include parameters to measure the power savings performance. Since the power savings objective influences selection of a network to handover to, the number of handovers is a parameter included to measure handover performance of the proposed NAHO variants.

7.3.1 Power Savings Performance

To analyze the performance of power savings for all the NAHO variants, the following parameters are chosen:

- *Remaining energy level of the MBU*: This parameter represents the amount of *remaining energy* in the MBU battery at the end of simulation. The higher is this value; the better is the power savings performance of corresponding NAHO variant. It is assumed that the simulations do not last long enough to completely drain the MBU battery.
- *Estimated battery depletion time*: This is the time calculated in seconds based on the remaining energy level of the MBU till its energy level will reach 10% if the simulation is continued. This value is calculated based on the simulation duration and the amount of MBU energy spent during the simulation run. A NAHO variant is better if it results in higher estimated battery depletion time compared to other variants.

7.3.2 Network Performance

To get an estimate of the goodput and RTT provided by the selected wireless network, we include the following network performance parameters similar to those in Section 6.4.1.

- *Average Biosignals Delivery Goodput:* This is an average amount of biosignals transferred for a given signal profile using the selected wireless network during a mobile patient monitoring session.
- *Average Keep-alive RTT:* The Keep-alive RTT is an observed round trip time of the extra-BAN communication path between the MBU and the surrogate host.
- *Average Monitoring Service Buffer Fill Level:* Since the monitoring service buffer fill level is an indicator of the number of biosignal data packets awaiting their transmission, it is also one of the indicators of goodput. The lower the buffer fill level, the higher is the goodput.
- *Average Biosignals Data Loss:* This is an average amount of data lost over simulation period. Data loss occurs only when the monitoring service buffer is full and can't accommodate more data. As described in Section 2.6, when the packets accumulated in the monitoring service buffer exceed a certain configurable *threshold* value, then older biosignals packets are removed to accommodate newer biosignals packets.

7.4 Simulation Setup

The simulation environment for evaluating the power savings aspect of the NAHO variants is same as that for evaluating NAHO mechanism proposed in Chapter 6. We use the *QoSCS simulator* for providing QoS predictions and *user trip simulator* for modeling geographic user movements. For the details of these two simulators, we refer to Section 6.5.

7.4.1 Simulation Parameters and Experiment Runs

In this section, we describe simulation parameters and experiment runs for the set of experiments which aim at comparing NAHO variants described in Section 7.2.2 among each other. These variants are *NAHO*, $NAHO_{WLAN\text{-}OFF}$, and $NAHO_{WLAN\text{-}OFF,WWAN\text{-}OFF}$; respectively. The simulation environment considers two types of wireless networks namely WiFi (WLAN) and GPRS (WWAN). The considered geographic topology, monitoring service QoS requirements and parameters related to the WLAN and WWAN networks are same as those described in Section 6.5. The QoSCS simulator obtains a list of approximately 2000 businesses from the Google maps server covering a geographic area with the radius of 70 km around *Geneva (Switzerland)* city centre and 802.11b base stations are assigned to these locations. For the user trip simulator, the trip originates at *Carouge* and ends at *Vernier* (both are municipalities in the *Canton of Geneva*) via *Geneva city centre* covering a distance of 8.470 km at the speed of 40 kmph and consisting of 107 sub-steps. (A sub-step consists of a transition from one step to another. This roughly corresponds to the change of street direction.) The goodput and RTT requirements of the biosignals delivery are *25580 bps* and *500 msec* respectively.

Two handheld mobile devices as MBUs

For the simulation experiments, we consider two handheld mobile devices (PDAs) namely a QTEK 9090 and an IPAQ. The NI power consumption values for these devices are taken from the experiments conducted in [Barg07 and Wac09a]. These two are different sets of experiments. Hence herewith we provide a brief description of those.

The experiments in [Wac09a] were conducted to obtain data about the power consumption of a mobile device used as MBU in the MHPMS. The MBU device is QTek 9090 and it has one WWAN-GPRS NI and one WLAN-WiFi (IEEE 802.11b) NI which can be used for extra-BAN communication. During the experimental conditions in [Wac09a], the MBU is initially fully charged. The QTEK 9090 battery is a rechargeable Li-ion Polymer of capacity of 1490 mAh (3.7V, model PH26B). According to these specifications this type of battery is expected to store total energy of 19847 Joules. The backlight of MBU touch screen display was turned off and particular NI state combinations (shown in Table 7.1) were chosen to transmit data packets. The MBU power consumption is measured by logging the remaining battery percentage in every 5 seconds interval. The duration of time after which the remaining battery percentage reaches 10% level (90% power of the MBU is consumed) is recorded. The NI state combination where both of the NIs are in the OFF state represents the base power consumption state of QTEK 9090. In the base power consumption state only BlueTooth NI is active obtaining biosignals from the sensor set (i.e. no biosignal data is sent to the back-end system). We do not consider the power consumption values for the NI state combination `[ON-ACTIVE, ON-ACTIVE]`, because in the existing implementation of MSP, it is not possible to use two NIs simultaneously for the biosignals delivery.

The experiments to measure NI power consumption of two devices namely QTEK 9090 device and IPAQ device are reported in [Barg07]. The difference between the QTEK 9090 device and IPAQ device is that the QTEK 9090 device has an integrated 802.11b NI card, while the IPAQ device had an external SDIO (*Secure Digital Input Output*) card for the IEEE 802.11b interface. The experimental conditions described in [Barg07] are similar to those in [Wac09a]. The backlight of MBU touch screen display was turned off and a particular NI state combination was chosen. In the ON-ACTIVE state, dummy data packets were sent. The experiments were run until either the remaining energy level of the IPAQ device fell below 25% or a period of 6 hours elapsed [Barg07].

In [Wac09a], the NI power consumption values are reported in terms of *energy-draining rate* per minute. In [Barg07], the NI power consumption values are reported in terms of the value of *slope of straight line* depicting decrease in the energy with increase in time – which also represents the *energy draining rate*. Given the amount of energy in a fully charged battery and the *energy drain rate* of NI power consumption, the values of NI power consumed per second are obtained (in Joules/Sec) for the NI state combinations of these devices (listed in Table 7.7). These values are rounded off to two decimal places. In this table we observe that the QTEK 9090 and IPAQ devices have different NI power consumption characteristics. E.g., for the QTEK 9090, a GPRS NI consumes more power than the WLAN NI in an ON-ACTIVE state, which is an opposite case compared to the IPAQ device.

Table 7.7: Network interface power consumption values for two devices namely QTEK 9090 and IPAQ

NI State Combination		*Power Consumed (Watt)*	
GPRS (WWAN)	**802.11b (WLAN)**	**QTEK**	**IPAQ**
OFF	OFF	0.30	0.30
OFF	ON-IDLE	0.38	1.16
OFF	ON-ACTIVE	1.81	1.66
ON-IDLE	OFF	0.35	0.33
ON-IDLE	ON-IDLE	0.44	1.18
ON-IDLE	ON-ACTIVE	1.86	1.71
ON-ACTIVE	OFF	1.95	1.44
ON-ACTIVE	ON-IDLE	2.04	2.29

In addition to these values, for simulating the *Powering ON* state of NI, we assume the NI activation duration and power consumption values shown in Table 7.8. The values of NI activation duration are obtained from the log of these events as recorded in the MCHO mechanism experiments. The value of WLAN NI Powering-ON state power consumption is measured in [Barg07]. For the simulation purposes, we consider the same value for the Powering ON state of GPRS NI as well as the values for the Powering ON state of GPRS NI could not be obtained.

Table 7.8: Network interface powering ON state power consumption values and activation duration

Network Interfaces	Powering ON state power consumption (Watt)	Activation Duration (in milliseconds)
WLAN	1.16	3830
GPRS	1.16	4000

Power savings preferences and initial battery power levels

To study the effect of power savings preference value we considered five power preference values (1, 2, 3, 4 and 5) which are mapped to the corresponding power savings objective values (0, 25, 50, 75 and 100 respectively – See Table 7.4). The weight of the AHP optimization objectives are calculated according to the AHP algorithm described in Section 7.2.3. Moreover, we also consider four initial battery power levels (25%, 50%, 75%, 100%) for both of the devices to analyze the amount of battery power savings that can be achieved for each of these power levels. Thus, in total 40 simulation runs are conducted considering that the NI power consumption values of two devices are used for the simulations.

7.5 Simulation Results and Their Interpretation

The results presented in this section are grouped into following four sections: 1) power savings performance; 2) network performance; and 3) objective-wise performance comparison of the following three AHP optimization objectives: *goodput objective*, *RTT objective* and *power savings objective*. The handover performance results are also included in Section 7.5.1 as they are useful to analyze power savings performance results. Considering that the NI power consumption data of two mobile devices was used and these devices have different power consumption characteristics, the performance results of these two devices are presented separately. The performance of the NAHO variants ($NAHO_{WLAN\text{-}OFF,}$ and $NAHO_{WLAN\text{-}OFF,WWAN\text{-}OFF}$) is compared with the NAHO mechanism.

7.5.1 Power Savings Performance Comparison Results

The results presented in this section show relative difference (in %) between the values of power savings performance parameters (Section 7.3.1) obtained for the NAHO variants with respect to the NAHO mechanism. These parameters are *remaining energy level* and *estimated depletion time*. Considering that V1, V2 and V3 are values of a parameter obtained for the NAHO mechanism, $NAHO_{WLAN\text{-}OFF,}$ variant and $NAHO_{WLAN\text{-}OFF,WWAN\text{-}OFF}$ variant respectively, the following simple equation determines relative performance difference (in %) between the $NAHO_{WLAN\text{-}OFF,}$ variant and NAHO mechanism: (V2 – V1) / V1 * 100. Similarly, the relative performance difference (in %) between the $NAHO_{WLAN\text{-}OFF,WWAN\text{-}OFF,}$ variant and NAHO mechanism is given by equation: (V3 – V1) / V1 * 100.

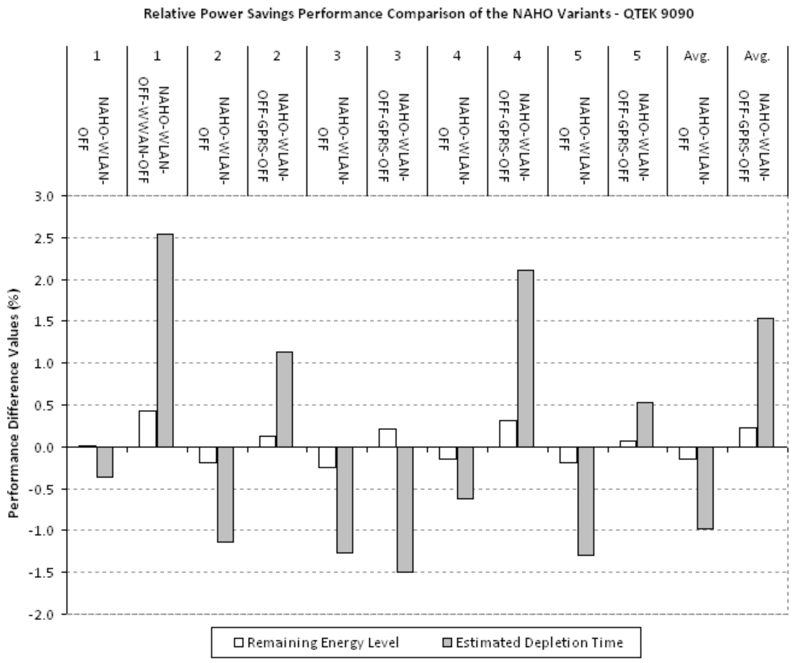


Figure 7.4: Relative power savings performance comparison of the NAHO variants – QTEK 9090 device

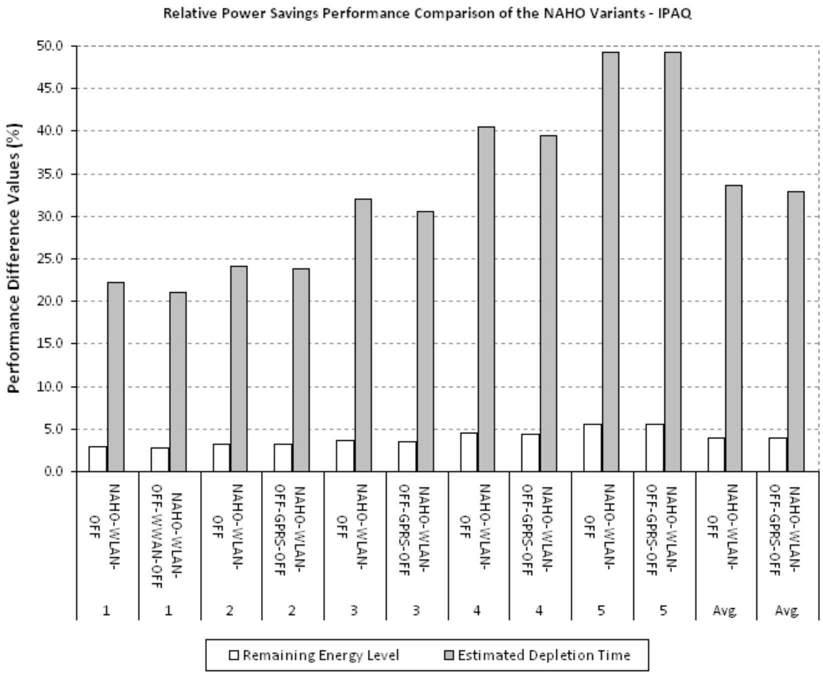


Figure 7.5: Relative power savings performance comparison of the NAHO variants – IPAQ device

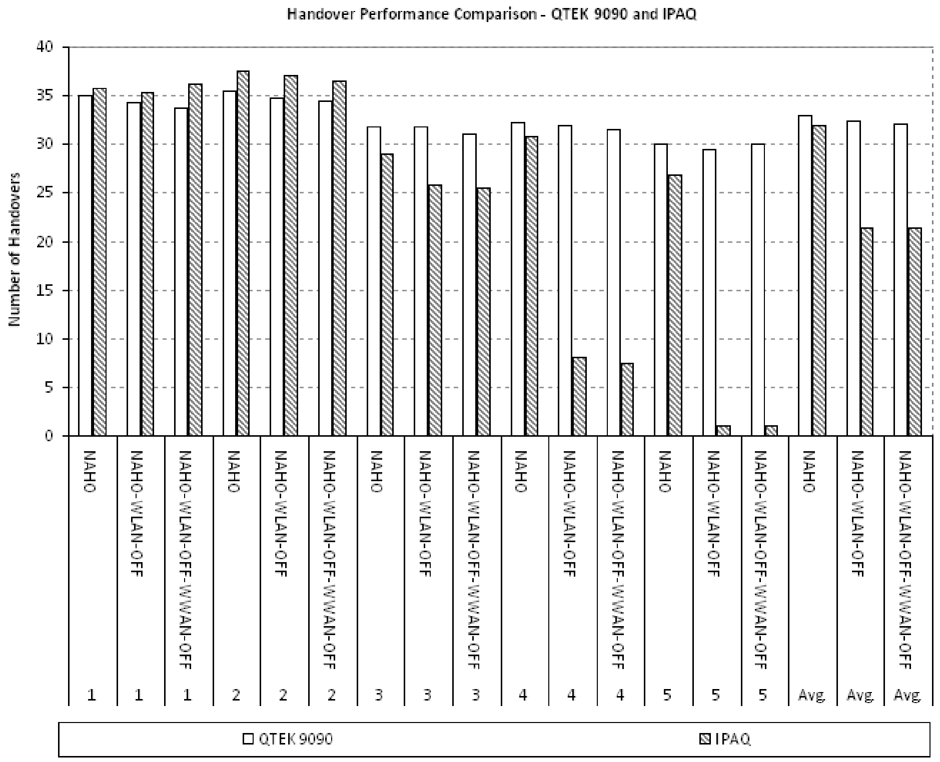


Figure 7.6: Number of vertical handovers of the NAHO mechanism and NAHO variants – QTEK 9090 and IPAQ devices

The graph in Figure 7.4 shows relative power savings performance of the NAHO variants compared to the NAHO mechanism for the QTEK 9090 device. Similarly, the graph in Figure 7.5 shows relative power savings performance of the NAHO variants with respect to the NAHO mechanism for the IPAQ device. On the X axis, the number shown next to the name of NAHO variant represents a value of *power savings preference* (from 1 to 5). The values of performance parameter for the averaged power savings preference are shown as well. From the data presented in Figure 7.4, it can be observed that on the QTEK 9090 device, the $\text{NAHO}_{\text{WLAN-OFF,WWAN-OFF}}$ variant shows minute amount of power savings compared to the NAHO mechanism. The average recorded increase in the remaining energy level is 0.2% and the estimated depletion time has increased by an average of 1.5%. In contrast, the $\text{NAHO}_{\text{WLAN-OFF}}$ variant shows on average 0.2% decrease in the remaining energy level and the estimated depletion time has decreased by an average of 1%.

The poor power savings performance of the $\text{NAHO}_{\text{WLAN-OFF}}$ variant for the QTEK 9090 device is explained by the fact that the NI state combination {WWAN ON-ACTIVE, WLAN ON-IDLE} state consumes only 4.6% higher amount of power compared to the NI state combination {WWAN ON-ACTIVE, WLAN OFF}. The initial state combination is applicable for the NAHO mechanism, while the latter NI state combination is applicable for the $NAHO_{WLAN-OFF}$ variant. The accumulated amount of energy saved by the $NAHO_{WLAN-OFF}$ variant is further compensated by the amount of energy required to activate WLAN NI in order to use the WLAN network. The minute 0.2% increase in the remaining energy level of the $NAHO_{WLAN-OFF,WWAN-OFF}$ variant is due to the reason that the NI state combination {WWAN OFF, WLAN ON-ACTIVE} state consumes 2.7% lower amount of energy compared to the NI state combination {WWAN ON-IDLE, WLAN ON-ACTIVE}. The initial state combination is applicable for the $NAHO_{WLAN-OFF,WWAN-OFF}$ variant, while the latter NI state combination is applicable for the $NAHO_{WLAN-OFF}$ variant. Since the battery level measurement tool used during the experimentation in [Wac09a] logs remaining energy level of the MBU battery in integer (no fractions supported), we conclude that no power savings can be achieved for the QTEK 9090 device.

From the data presented in Figure 7.5, it can be observed that on the IPAQ device, both of the NAHO variants result in power savings compared to the NAHO mechanism. For the $NAHO_{WLAN-OFF}$ variant, on an average 4% increase in the remaining energy level is recorded and the value of an estimated depletion time has increased by an average of 33.6%. The performance of the $NAHO_{WLAN-OFF,WWAN-OFF}$ variant is similar to the $NAHO_{WLAN-OFF}$ variant. For the $NAHO_{WLAN-OFF,WWAN-OFF}$ variant, on an average 3.9% increase in the remaining energy level is recorded and the estimated depletion time has increased by an average of 32.9%. For the IPAQ device, the NI state combination {WWAN ON-ACTIVE, WLAN ON-IDLE} state consumes 59% higher amount of energy compared to the NI state combination {WWAN ON-ACTIVE, WLAN OFF}. In this case, it is observed that the accumulated amount of energy saved by the $NAHO_{WLAN-OFF}$ variant is higher than the amount of energy required to power on WLAN NI.

The positive power savings performance of the NAHO variants on the IPAQ device is attributed to lower power consumption of WWAN NI in the ON-ACTIVE state (1.44 watts) compared to the power consumption of WLAN NI in the ON-ACTIVE state (1.66 watts). As seen from Table 7.7, the QTEK 9090 device has opposite characteristics compared to the IPAQ device. On the QTEK 9090 device, the power consumption of WWAN NI in the ON-ACTIVE state (1.95 watts) is higher than the power consumption of WLAN NI in the ON-ACTIVE state (1.81 watts). For the IPAQ device, it is observed that the AHP decision making algorithm tends to use the WWAN NI more frequently than the WLAN NI. Since the WWAN network is ubiquitously available and the use of WWAN NI results in less power consumption, it is a preferred network for the handover. This trend is not observed for the QTEK 9090 device. The graph in Figure 7.6 shows the number of handovers for both of the devices. From the number of handovers data presented in Figure 7.6, it is observed that when the value of power savings preference is four, on the IPAQ device both of the NAHO variants record eight handovers. For the value of power savings preference 5, both of the NAHO variants record only one handover.

Together considering the results obtained for both the devices and compared to the NAHO mechanism, it is observed that using the proposed AHP decision making and QoS predictions, the power savings is observable on the type of mobile devices which are characterized by lower power consumption of the WWAN NI compared to the WLAN NI. For the mobile devices characterized by higher power consumption of the WWAN NI compared to the WLAN NI, no power savings is observed.

7.5.2 Network Performance Comparison Results

The results presented in this section show relative performance difference (in %) between the values of network performance parameters (Section 7.3.2) obtained for the NAHO variants with respect to the NAHO mechanism. These parameters are *average biosignals delivery goodput*, *average biosignals data loss*, *average monitoring service's buffer fill level* and *average keep-alive RTT*. Considering that V1, V2 and V3 are values of a performance parameter obtained for the NAHO mechanism, $NAHO_{WLAN\text{-}OFF,}$ variant and $NAHO_{WLAN\text{-}OFF,WWAN\text{-}OFF}$ variant respectively, the following simple equation determines relative performance difference (in %) between the $NAHO_{WLAN\text{-}OFF,}$ variant and NAHO mechanism: (V2 – V1) / V1 * 100. Similarly, the relative performance difference (in %) between the $NAHO_{WLAN\text{-}OFF,WWAN\text{-}OFF,}$ variant and NAHO mechanism is given by equation: (V3 – V1) / V1 * 100.

The graph in Figure 7.7 shows relative network performance of the NAHO variants compared to the NAHO mechanism for a QTEK 9090 device. Similarly, the graph in Figure 7.8 show relative network performance of the NAHO variants compared to the NAHO mechanism for an IPAQ device. On the X axis, the number shown next to the name of a NAHO variant represents value of *power savings preference* (from 1 to 5). The values of performance parameter for the averaged power savings preference are shown as well. From the data presented in Figure 7.7 and Figure 7.8, it can be observed that both of the NAHO variants result in poor network performance compared to the NAHO mechanism. Among these two variants, the $NAHO_{WLAN\text{-}OFF}$ variant performs better compared to the $NAHO_{WLAN\text{-}OFF,WWAN\text{-}OFF}$ variant.

The reduced network performance of the NAHO variants for the QTEK 9090 device is attributed to the lower amount of time spent by both the NIs in the ON-ACTIVE state compared to the NAHO mechanism. In the ON-ACTIVE state the MBU NI transmits biosignals data. For the QTEK 9090 device, the data presented in Figure 7.9 shows relative time difference values of the NI ON-ACTIVE state for both the variants compared to the NAHO mechanism. From this graph, it can be seen that for the $NAHO_{WLAN\text{-}OFF}$ ($NAHO_{WLAN\text{-}OFF,WWAN\text{-}OFF}$) variant the average amount of time for which the WWAN NI is in ON-ACTIVE state is 2.3% (6.3%) lower than the NAHO variant. Further, for the $NAHO_{WLAN\text{-}OFF}$ ($NAHO_{WLAN\text{-}OFF,WWAN\text{-}OFF}$) variant the average amount of time for which the WLAN NI is in ON-ACTIVE state is 4.4% (5.2%) lower than the NAHO variant. The corresponding relative difference in the values of network performance parameters is shown in Table 7.9.

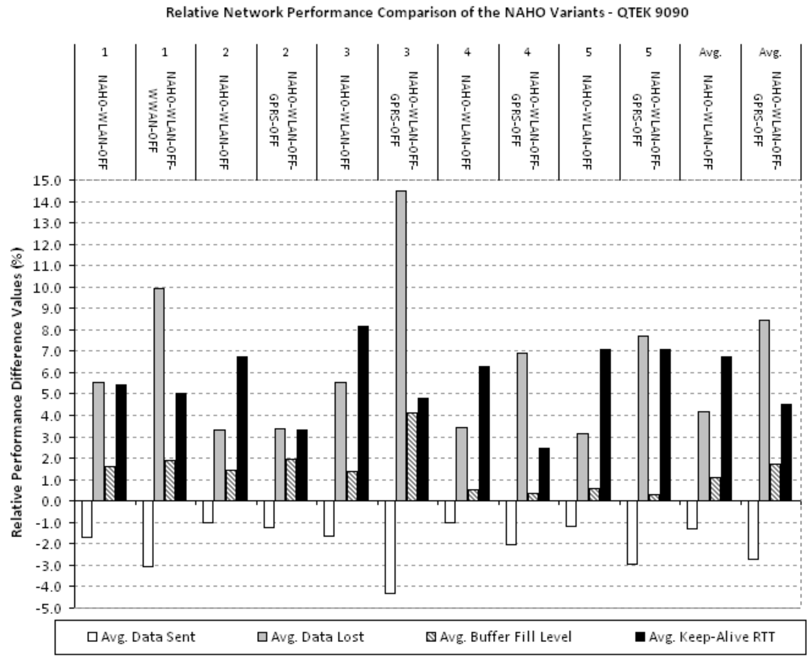


Figure 7.7: Relative network performance comparison of the NAHO variants – QTEK 9090 device

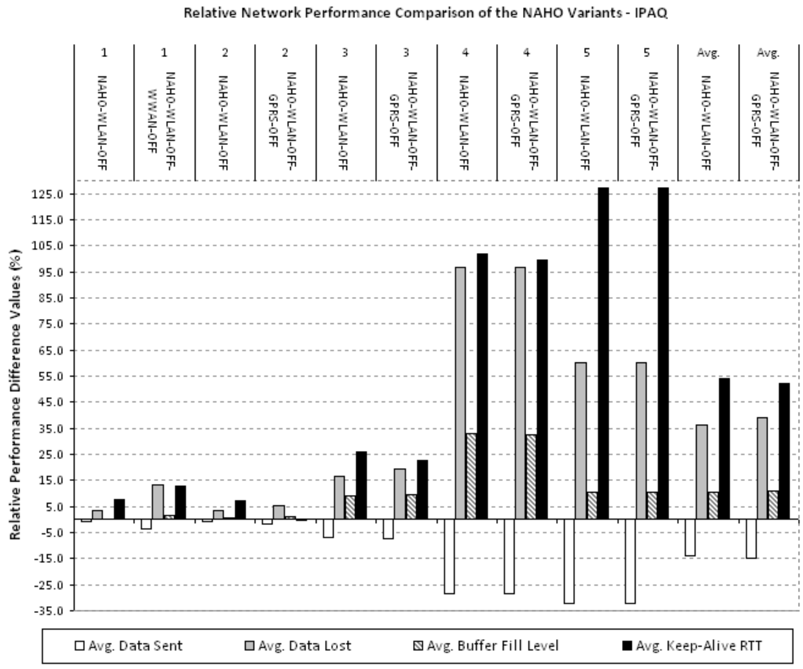


Figure 7.8: Relative network performance comparison of the NAHO variants – IPAQ device

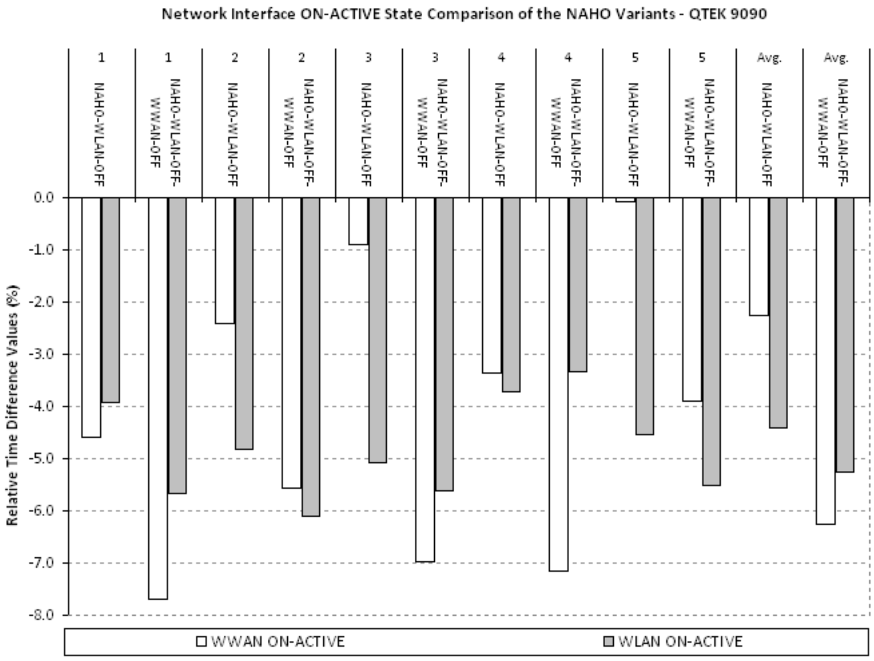


Figure 7.9: Relative NI ON-ACTIVE state comparison of the NAHO variants – QTEK 9090 device

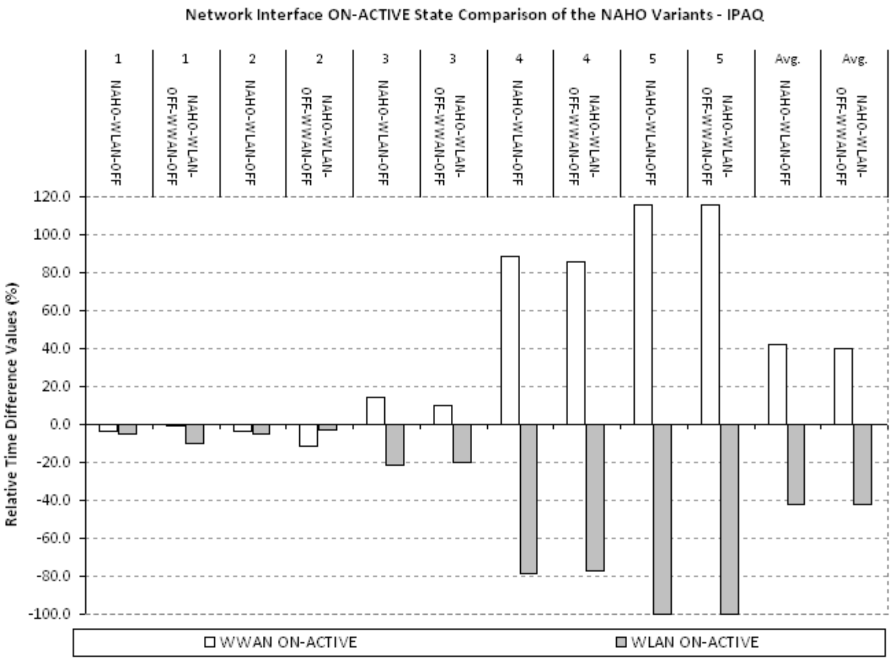


Figure 7.10: Relative NI ON-ACTIVE state comparison of the NAHO variants – IPAQ device

The reduced network performance of the NAHO variants for an IPAQ device is attributed to the higher amount of time spent by the WWAN NI in the ON-ACTIVE state and lower amount of time spent by the WLAN NI in the ON-ACTIVE state. Traditionally, the WWAN networks provide lower QoS compared to the WLAN networks. For the IPAQ device, the data presented in Figure 7.10 shows relative time difference values of the NI ON-ACTIVE state for both the variants compared to the NAHO mechanism. From this graph, it can be seen that for the $NAHO_{WLAN\text{-}OFF}$ ($NAHO_{WLAN\text{-}OFF,WWAN\text{-}OFF}$) variant the average amount of time for which the WWAN NI is in ON-ACTIVE state is 42.3% (39.9%) higher than the NAHO variant. Further, for the $NAHO_{WLAN\text{-}OFF}$ ($NAHO_{WLAN\text{-}OFF,WWAN\text{-}OFF}$) variant the average amount of time for which the WLAN NI is in ON-ACTIVE state is 41.9% (42%) lower than the NAHO variant. The corresponding relative difference in the values of network performance parameters is shown in Table 7.10.

Table 7.9: Relative NI ON-ACTIVE state comparison and corresponding network performance difference compared to the NAHO mechanism – QTEK 9090 device

Variant	WWAN ON-ACTIVE	WLAN ON-ACTIVE	Avg. Data Sent	Avg. Data Loss	Avg. Buffer Fill Level	Avg. Keep-Alive RTT
$NAHO_{WLAN\text{-}OFF}$	-2.3%	-4.4%	-1.3%	4.2%	1.1%	6.8%
$NAHO_{WLAN\text{-}OFF,WWAN\text{-}OFF}$	-6.3%	-5.2%	-2.7%	8.5%	1.7%	4.5%

Table 7.10: Relative NI ON-ACTIVE state comparison and corresponding network performance difference compared to the NAHO mechanism – IPAQ device

Variant	WWAN ON-ACTIVE	WLAN ON-ACTIVE	Avg. Data Sent	Avg. Data Loss	Avg. Buffer Fill Level	Avg. Keep-Alive RTT
$NAHO_{WLAN\text{-}OFF}$	42.3%	-41.9%	-13.9%	36.1%	10.6%	54%
$NAHO_{WLAN\text{-}OFF,WWAN\text{-}OFF}$	39.9%	-42%	-14.7%	39%	11.1%	52.4%

7.5.3 AHP Tradeoffs between the Power Savings Performance and Network Performance

The research objective 5 of this thesis is: *What are the gains achieved by the proposed vertical handover mechanisms and what are the corresponding overheads?* The proposed context-aware vertical handover approaches for the MHPMS are aimed at handling changes in the availability of wireless networks, provide sufficient extra-BAN communication QoS for the biosignals delivery and minimize power consumption on the MBU. The AHP algorithm in the NAHO mechanism (Section 7.2.3) decides the weights of objectives named *satisfy goodput*, *satisfy RTT* and *maximize power savings* based on the value of *power savings preference*. The combined sum of these objective weights is always 1. The power savings preference may take any value between (1, 2, 3, 4 and 5) in the increasing order of importance of the maximize power savings objective. To represent the performance of these objectives, we use following performance metrics in this section: *average data sent*, *average keep-alive RTT* and *remaining power* respectively.

The graphs in Figure 7.11 show objective-wise performance comparison of NAHO mechanism, $NAHO_{WLAN\text{-}OFF}$ variant and $NAHO_{WLAN\text{-}OFF,WWAN\text{-}OFF}$ variant respectively for the QTEK 9090 device. The graphs in Figure 7.12 show objective-wise performance comparison of NAHO mechanism, $NAHO_{WLAN\text{-}OFF}$ variant and $NAHO_{WLAN\text{-}OFF,WWAN\text{-}OFF}$ variant respectively for the IPAQ device. For considering the impact of increase in the power savings preference, the values of power savings objective, goodput objective and RTT objective are considered 1 for the power savings preference value 1. The obtained performance parameter values of these objectives for the higher values of power savings preference (2, 3, 4, 5) are converted into respective ratios (on the Y axis of graphs).

From the graphs shown in Figure 7.11 it is observed that on the QTEK 9090 device, the NAHO mechanism and both of the NAHO variants demonstrate a trend as follows: The increase in the value of power savings preference has no effect on the performance of power savings objective. For the higher values of the power savings preference, the performance of goodput objective has slightly improved (2% on average). Also, for the higher values of power savings preference, the performance of RTT objective has improved (4% on average). This means that on the QTEK device, the increase in the value of power savings objective did not have any adverse effect on the performance of goodput objective and RTT objective. This behavior is due to the power consumption characteristics of the WLAN NI. Since on the QTEK 9090 device, the WLAN NI consumes less amount of power than the WWAN NI in the ON-ACTIVE state, it has a higher chance of selection with the increase in the power savings preference value.

From the graphs shown in Figure 7.12 the following trends are observed on the IPAQ device: For the NAHO mechanism, the increase in the power savings preference has no effect on the power savings objective. For the NAHO variants, with the increase in the power savings preference, the performance of power savings objective has slightly improved (1% on average). For the higher values of power savings preference, the performance of goodput objective has degraded (8% on average). In case of the goodput objective; an exception is noted when the value of power savings preference is 5 – where the goodput objective performance has slightly increased. However, for the higher values of power savings preference, the RTT objective performance has degraded considerably i.e. higher values of keep-alive RTT are obtained (57% on average degradation for the $NAHO_{WLAN\text{-}OFF}$ variant and 49% on average degradation for the NAHOWLAN-OFF-WWAN-OFF variant). Considering these results, it is concluded that on the IPAQ device, the increase in the value of power savings preference has a positive effect on the performance of power savings objective and adverse effect on the performance of goodput objective and RTT objective. This behavior is due to the power consumption characteristics of the WWAN NI – which has a higher chance of selection due to its lower power consumption than the WLAN NI.

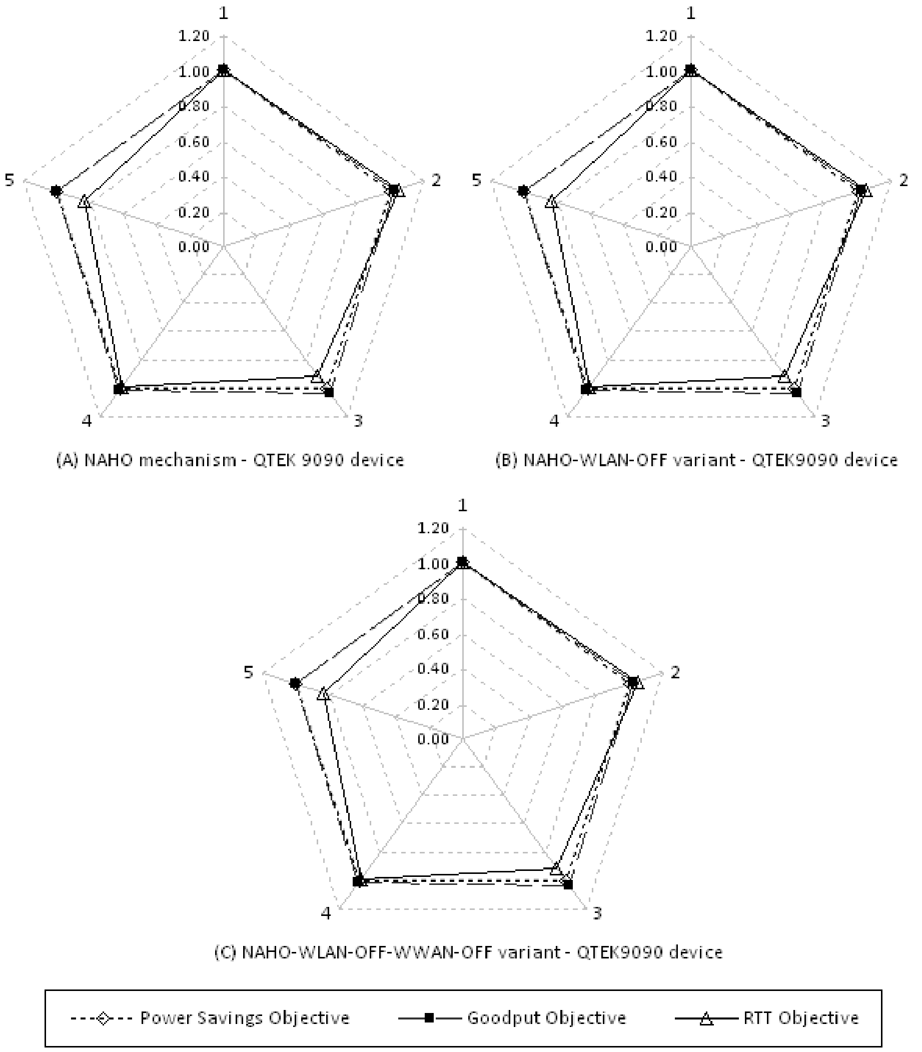


Figure 7.11: Objective-wise performance comparison of the NAHO mechanism and NAHO variants vs. power savings preference value - QTEK 9090 device

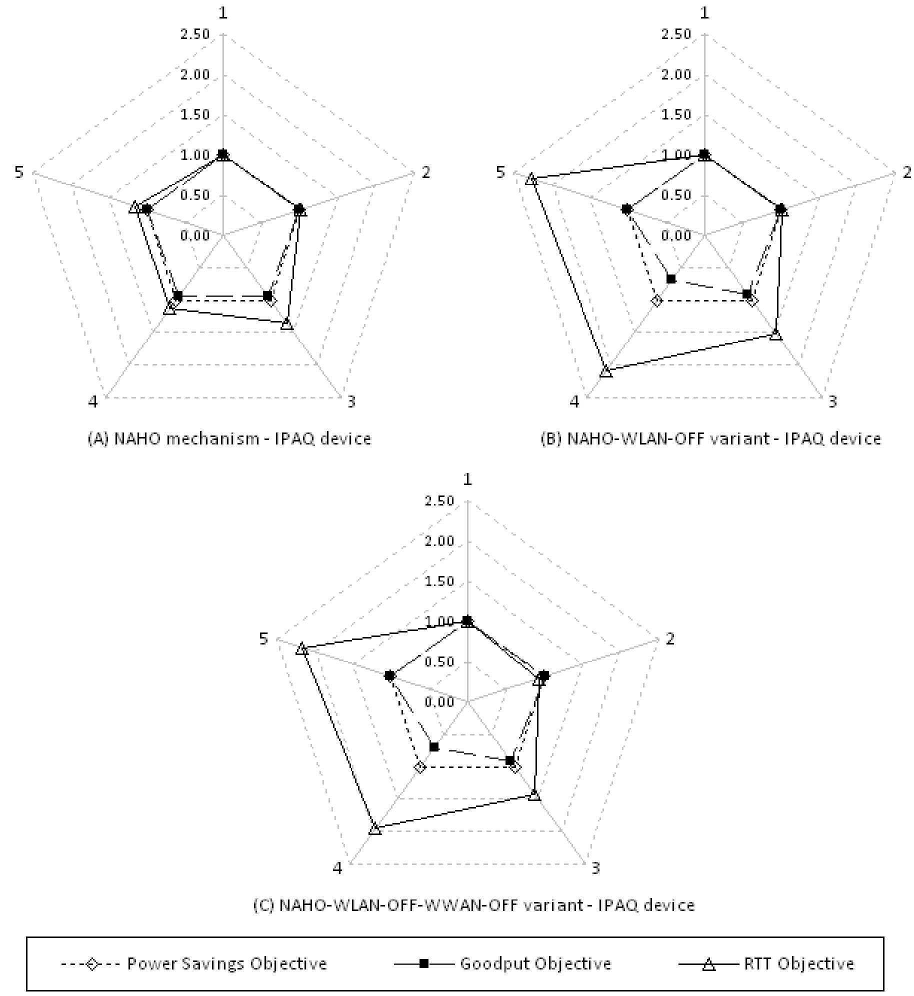


Figure 7.12: Objective-wise performance comparison of the NAHO mechanism and NAHO variants vs. power savings preference value - IPAQ device

7.6 Chapter Conclusion

The research reported in this chapter is conducted to address research objective 4 of this thesis which is: *How to use the wireless network interfaces of the MBU to reduce its power consumption during the continuous delivery of biosignals?* In the MHPMS, a MBU is solely used for patient monitoring purposes. The intra-BAN communication part of MBU is used to obtain biosignals and perform biosignals related processing. Since a significant amount of power is consumed by the MBU network interfaces (NIs) for biosignals delivery, we decided to assess the possibility of power savings on the MBU by switching off the unused NI of the MBU as motivated from [Chen05].

From the data transfer perspective, at any given time, the NI of a MBU is in one of the following states: 1) *OFF*: No IP connectivity; 2) *POWERING-ON:* This is an intermediate state required to switch on the NI; 3) *ON-IDLE*: an *IP-idle* state, where the NI has IP connectivity to the Internet. However it does not send/receive any IP packets carrying biosignals data; and 4) *ON-ACTIVE*: an IP-active state, where the MBU is sending or receiving application level IP packets through this NI. Considering that a typical mobile device used as MBU has at least two NIs – one for using WWAN connectivity and the other for using WLAN connectivity respectively, we proposed two NAHO variants of the NAHO mechanism as follows:

- ***NAHO***$_{WLAN\text{-}OFF}$**:** This is the NAHO mechanism in which the WWAN NI is always powered on. However, if the WLAN NI is not in use for the biosignals delivery, then it is powered off.
- ***NAHO***$_{WLAN\text{-}OFF,WWAN\text{-}OFF}$**:** This mechanism is an extension of the NAHO$_{WLAN\text{-}OFF}$ variant. IN this variant, if the WWAN (WLAN) network is selected for biosignals delivery, then the WLAN (WWAN) NI is switched off.

Compared to these variants, in the NAHO mechanism no NI is in the OFF state during the biosignals transmission. To be able to take a power-aware network selection decision, the context information about power consumption characteristics of the MBU is necessary. Hence we augmented the architecture of the NAHO mechanism to use a power context source and related context processor and context reasoner information processing. Specifically:

1) An additional context source named power CS is included to provide the following context information: *maximum battery capacity of the MBU, remaining battery power of the MBU (in %)*, *power consumption in Joules/Sec by a combination of network interface states* and *the power savings preference* in a range of 1-5 (from the least important to the most important).
2) The context processor component includes context information provided by the power CS in the context snapshot and it handles an additional context change that signifies change in the remaining battery power of the MBU.
4) The AHP network selection algorithm of the NAHO mechanism is extended to consider a *power savings objective* in addition to the *goodput objective* and *RTT objective*. To determine the effect of power savings on the goodput and the RTT, the AHP algorithm assigns weight to the goodput objective and RTT objective depending

on the value of power savings preference (from 1 to 5 in the increasing order of importance). On the occurrence of every context change event, the context reasoner evokes AHP algorithm for selecting a wireless network that *satisfies monitoring service's goodput requirements*, *satisfies monitoring service's RTT requirements* and *minimizes power consumption of the MBU*.

The simulation setup for the experiments is similar to the simulation setup described in Chapter 6 with the following additions. We consider four initial battery power levels (25%, 50%, 75%, 100%) for both of the devices because the patient is not usually aware of the current battery power level. The experiments considered NI power consumption values of two PDA devices namely QTEK 9090 and IPAQ. These devices have different NI power consumption characteristics. In the experimental mobile patient monitoring scenario, it is assumed that a patient travels a distance of 8.470 kms at the speed of 40 km/h. The *user trip simulator* was used to generate user movements during the course of simulation. The *QoS CS Simulator* was used to provide QoS predictions to the MBU. This performance evaluation was conducted for the cardio biosignals profile which has following biosignals delivery requirements – goodput requirements: *28472 bps* and RTT requirements: *500 ms.*

The results shown in Table 7.11 compare the AHP optimization objective-wise performance of the NAHO variants with the NAHO mechanism for two mobile devices used – QTEK 9090 and IPAQ. For the objective-wise performance data presented in Table 7.11, we represent these objectives by the performance metrics *average data sent*, *average keep-alive RTT* and *remaining battery power* respectively.

Table 7.11: Statistics showing objective-wise performance difference between the NAHO variants and NAHO mechanism

Objective	Relative Performance Difference QTEK 9090 device		Relative Performance Difference IPAQ device	
	$NAHO_{WLAN-OFF}$ and NAHO	$NAHO_{WLAN-OFF,WWAN-OFF}$ and NAHO	$NAHO_{WLAN-OFF}$ and NAHO	$NAHO_{WLAN-OFF,WWAN-OFF}$ and NAHO
Goodput objective	-1.3 %	-2.7 %	-13.9 %	-14.7 %
RTT objective	6.8 %	4.5 %	54 %	52.4 %
Power Savings objective	-0.2 %	0.2 %	4 %	3.9 %

From the data presented in Table 7.11, it can be observed that on the QTEK 9090 device, the $NAHO_{WLAN-OFF}$ variant records 0.2% more power consumption compared to the NAHO variant, while $NAHO_{WLAN-OFF,WWAN-OFF}$ variant shows 0.2% power savings. Since the battery level measurement tool used during the experimentation in [Wac09a] logs remaining energy level of the MBU battery in integer (no fractions supported), we conclude that no power savings is achieved for the QTEK 9090 device. In comparison, the power savings was observed on the IPAQ device, where the $NAHO_{WLAN-OFF}$ variant records 4% power savings compared to the

NAHO variant, while $NAHO_{WLAN\text{-}OFF,WWAN\text{-}OFF}$ variant shows 3.9% power savings. The positive power savings performance on the IPAQ device is attributed to the lower power consumption of WWAN NI in the ON-ACTIVE state (1.44 watts) compared to the power consumption of WLAN NI in the ON-ACTIVE state (1.66 watts).

On both of the devices, the NAHO variants record lower goodput performance and lower RTT performance compared to the NAHO mechanism. On the QTEK 9090 device, this QoS performance degradation is attributed to lower amount of time spent by both the NIs in ON-ACTIVE state as compared to the NAHO mechanism. On the IPAQ device the QoS performance degradation is attributed to higher amount of time spent by the WWAN NI in the ON-ACTIVE state and lower amount of time spent by the WLAN NI in the ON-ACTIVE state. The data in Table 7.12 shows relative difference in the time spent by the WWAN NI and WLAN NI in the ON-ACTIVE state compared to the NAHO mechanism. From Table 7.12, it is seen that for the IPAQ device, the AHP decision making algorithm tends to use the WWAN NI more frequently than the WLAN NI. Since the WWAN network is ubiquitously available and the use of WWAN NI results in lower power consumption, it is a preferred network for handover. This trend is not observed for the QTEK 9090 device.

Table 7.12: Relative difference in the time spent by the WWAN NI and WLAN NI in the ON-ACTIVE state compared to the NAHO mechanism

	QTEK 9090 device		IPAQ device	
Variant	**WWAN ON-ACTIVE**	**WLAN ON-ACTIVE**	**WWAN ON-ACTIVE**	**WLAN ON-ACTIVE**
$NAHO_{WLAN\text{-}OFF}$	-2.3 %	-4.4 %	42.3 %	-41.9 %
$NAHO_{WLAN\text{-}OFF,WWAN\text{-}OFF}$	-6.3 %	-5.2 %	39.9 %	-42 %

Together considering the results obtained for both devices and compared to the NAHO mechanism, it is observed that using proposed AHP decision making and QoS predictions, power savings is observable on the type of mobile devices which are characterized by lower power consumption of the WWAN NI compared to the power consumption of WLAN NI. For the mobile devices characterized by higher power consumption of the WWAN NI compared to the WLAN NI, no power savings is observed.

To understand the effect of power savings preference value on the goodput objective and RTT objective, we conducted further analysis of results. This analysis shows that on a QTEK 9090 device, the increase in value of power savings preference neither achieves any power savings nor affects the performance of goodput objective and RTT objective. On the IPAQ device, the increase in the value of power savings preference achieves power savings at the cost of adverse effect on the performance of goodput objective and RTT objective. In summary, the proposed AHP based QoS-aware and power-aware network selection mechanism is a suitable decision making technique for use in the proposed NAHO mechanism and NAHO variants.

Chapter 8

Conclusions and Future Work

In this thesis, we investigated several aspects related to the research areas of mobile patient monitoring and vertical handover. Specifically, we proposed and evaluated two context-aware vertical handover mechanisms which together address the wireless network connectivity problems resulting from patient mobility and select the wireless network that best satisfies QoS requirements of continuous biosignals delivery. Following a context-aware computing based approach, we also adapted proposed handover mechanism to use a wireless network interface the use of which reduces power consumption of a *Mobile Base Unit* (MBU) used in a mobile patient monitoring system. In this chapter, we present thesis conclusions and directions for the future work. This chapter is organized as follows. Section 8.1 presents conclusions of the thesis research objectives. Section 8.2 outlines the thesis contributions. Section 8.3 describes the future work.

8.1 Conclusions of Research Objectives

The research problem addressed by this thesis is the following:

In the MHPMS, for the mobile patient monitoring cases requiring continuous biosignals delivery to the back-end system, how to use a vertical handover technique to satisfy QoS requirements of biosignals delivery in the environment characterized by patient mobility, deployment of multiple wireless networks technologies, uneven geographic distribution of the wireless networks, variable QoS characteristics of the wireless networks and limited battery capacity of the MBU?

In Chapter 1, we split this research problem into five research objectives. In this section, we present conclusions of these research objectives.

8.1.1 Research Objective 1

The research objective 1 of this thesis is: *How to infer QoS requirements for the mobile patient monitoring cases requiring continuous biosignals delivery from the MBU to the back-end system?*

The QoS requirements of biosignals delivery are dependent on the following medical dimensions: *application purpose* and *application area*. The application purpose of the *MobiHealth Patient Monitoring System* (MHPMS)[28] is to enable patients to send full, detailed and accurate biosignals to the healthcare center and receive medical care irrespective of their location. The MHPMS application area considered in this thesis is the mobile patient monitoring scenarios in which patient biosignals are transmitted continuously using wireless network connectivity to the location of healthcare professional. For the healthcare professionals, in order to make an accurate decision about patient's condition, it is necessary that certain clinical requirements be fulfilled by the patient monitoring service. These requirements are the following: 1) Certain types of biosignals are must for the decision making; 2) The quality of biosignals being received should be at least good enough so that the decision making is not affected; 3) In case the decision taken expects the patient to take a certain action, then the feedback should be received by the patient to allow a certain reaction time. Since the telemedicine delivery dimensions [Tulu05] has a goal of supporting the needs of medical dimensions, these clinical requirements need to be considered by the patient monitoring service and supported by the wireless networks in the biosignals delivery path. In the mobile computing terms, these requirements are specified in terms of the *Quality of Service* (QoS) parameters. Based on the analysis of patient monitoring scenarios and the survey of QoS in the mobile computing environment [Chal99] we correlated these clinical requirements to the following QoS parameters *goodput*, *round trip time* (RTT) and *data loss ratio* respectively.

In this thesis, we analyzed three continuous mobile patient monitoring scenarios which are the following: HEARTRONIC mobile patient monitoring [Roch08], remote physiotherapy treatment [Ferg09] and MHPMS trauma patient transport [Alon02]. It is observed that the goodput requirements of biosignals delivery are dependent on the sample size of an individual biosignal and corresponding sampling frequency [Dima03]. In addition, compression factor if any also needs to be considered. The RTT requirements of the remote physiotherapy treatment [Ferg09] and trauma patient transport scenarios [Alon02] are correlated to the RTT requirements of the video conferencing service, since in both of these cases synchronous communication between both the ends (patient and healthcare professional) is necessary. Since the recommended maximum value of the one-way delay for video conferencing application is 150 ms [Ali05, Chen04], the two-way delay is 300 ms. On top of this, we assume that the human response time of a healthcare professional is 200 ms (e.g. a physician need to analyze current move).

[28] While preparing this manuscript, the MHPMS is acquired by MobiHealth B.V. and has undergone further innovations therein (http://www.mobihealth.com/).

Combining, the RTT value of 500 ms is assigned to the remote physiotherapy and trauma team cases. For the irregular ECG pattern detection case, the RTT requirements are not applicable as it is not required for a patient to receive immediate response from the healthcare professional. The *data loss ratio* for all the scenarios is considered zero based on the QoS evaluation of telemedicine network reported in [Zamb09]. In a recently reported e-Health QoS research [Skor10], the QoS requirements of e-Health applications are mapped onto the *Evolved Packet System* (EPS) QoS classes.

8.1.2 Research Objective 2

The research objective 2 of this thesis is: *How to use a vertical handover technique to maintain HTTP connectivity to the MBU in the events of patient mobility and network outage?*

The term vertical handover refers to a switchover from one network connection to another for the exchange of data. The vertical handover is used in the ubiquitous computing to realize *Always Best Connected* (ABC) concept, which refers to being connected in the best possible way in an environment of multiple wireless networks [Kass08]. The phases of a vertical handover technique to be used in a mobile application is specified in terms of a *handover management process* [Kass08] as follows: 1) *Handover information gathering* phase collects information required to identify the need for handover and initiate the handover; 2) *Handover decision making (network selection)* phase determines a suitable network for the handover execution; and 3) *Handover execution* phase performs an actual handover to the network selected in the second phase. From the literature survey [Balao4, Ahme06, Wu09, Chen05, Hong06, Vida05], it is observed that the vertical handover mechanisms are used to maintain wireless connectivity to the mobile device in the environment characterized by user mobility and the deployment of heterogeneous wireless and fixed networks (LAN, WLAN, GSM, UMTS, Wi-Fi, WiMAX). The vertical handover is performed at various levels of the OSI reference model – which are *link layer*, *IP layer*, *transport layer* and *application layer*. The wireless network QoS information and application's QoS requirements are used in all the approaches for taking a handover decision.

In order to support the functions of handover management process, solution architecture is required so that the vertical handover technique can be investigated for use in the mobile patient monitoring system. In the overview of vertical handover decision strategies presented in [Kass08], it is noted that context-aware computing based vertical handover architecture is highly efficient, highly flexible and supports both, real-time and non-real-time application services. Context-aware computing based vertical handover mechanisms are used in [Bala04, Ahme06] for the handheld mobile devices and they are validated for use on these devices. A vision of pervasive healthcare and wireless health monitoring elaborated in [Vars07] proposes that provisioning of the context-awareness in a wireless health monitoring system will be useful to aid in a better decision making by healthcare professionals. The use of context-aware computing approach for the mobile applications in the healthcare domain [Wegd05] is also envisioned in the AWARENESS project in which the reported work is conducted. Given this reasoning, context-aware computing is our architectural choice for supporting the tasks of vertical handover management process in the MHPMS.

In the proposed context-aware vertical handover mechanisms, the *context sources* are designed to provide the following types of handover information: *network related*, *MBU related* and *service related*. An entity called *context processor* is designed to address *handover information gathering* phase, thereby to retrieve real time context information and construct a unified view of context information for use in the *handover decision making* phase. The *context reasoner* is designed to perform the tasks of *handover decision making* phase. The *handover execution* phase i.e. the actual handover to the wireless network of choice is performed by the *Mobile Service Platform* middleware [Halt06] entities on the MBU responsible for initiating a HTTP connection to the MHPMS back-end and deliver biosignals data using a *HTTP chunking* technique.

In this thesis, we proposed two context-aware vertical handover mechanisms for use in the mobile patient monitoring systems. The first mechanism is the *mobile controlled handover* (MCHO) mechanism and the second mechanism is the *network assisted handover* (NAHO) mechanism. In principle, these two vertical handover mechanisms differ according to the placement and number of context sources. In the MCHO mechanism, a communication context source named COSPHERE [Pedd05] is used to obtain the following network QoS information: *wireless network technologies* (e.g. GSM, 802.11b), *maximum bandwidth capacity* and *IP addresses of the MBU network interfaces*. Since the WWAN networks (e.g. 802.11b) traditionally provide higher bandwidth than the WLAN networks (e.g. GPRS), the MCHO handover decision making selects a network with the highest maximum bandwidth capacity among the available networks.

In the NAHO mechanism it is envisioned that the wireless networks information (network technologies, geographic availability, goodput and RTT in the location and time dimensions) is reliably and accurately made available by a *QoS predictions context source*[29] which is hosted in the fixed network. The handover decision making in the NAHO mechanism is designed to rank wireless networks based on their offered QoS and QoS requirements of the biosignals delivery. In both of the proposed mechanisms, the handover execution phase is performed in the following two cases: 1) The MBU is not connected to any network at present – this situation may occur due to the patient mobility and/or network outage; and 2) When the network selected in the handover decision making phase provides higher QoS than the network currently in use by the MBU.

[29] The research on QoS predictions is ongoing and it is shown that it is possible to provide accurate estimates of RTT (81%) using machine learning techniques [Wac09b]

8.1.3 Research Objective 3

The research objective 3 of this thesis is: *If the information about QoS characteristics of the wireless networks at a given location and time are known, how to take a decision on the selection of the wireless network for the delivery of biosignals?*

According to the handover management process described in [Kass08], the *handover decision making (network selection)* phase determines a suitable network for the handover execution. The proposed NAHO mechanism has the aim to select a suitable wireless network based on their offered QoS (this information is provided by QoS predictions) and QoS requirements of the biosignals delivery.

Among the six vertical handover management approaches studied in the state of the art, five approaches [Bala04, Ahme06, Chen05, Hong06, Vida05] compare the application QoS requirements with the QoS provided by the wireless network in the handover decision making phase. We observed the following general sequence of the handover decision making phase for taking a context-aware network selection decision: 1) Determine a set of available wireless networks based on the user location; 2) Obtain the QoS values provided by these wireless networks; 3) Perform ranking of the wireless networks based on how well each network satisfies applications QoS requirements; and 4) Select the network with the highest rank for the handover.

In the proposed NAHO mechanism, the QoS predictions are periodically obtained by the context processor hosted on the MBU; so that the wireless networks availability and their QoS information is available locally. The current location of the MBU is obtained from the *location and time context source*[30]. A set of available wireless networks at a given location is determined by mapping the geographic coordinates of a user's current location onto the coverage area of the wireless network. The current wireless network QoS values are obtained by further processing QoS predictions in the time dimension. In the QoS predictions, the QoS of wireless network is represented in terms of the *goodput* and *RTT* parameters.

The QoS comparison based decision making in [Chen05] selects a wireless network that closely satisfies application's QoS requirements. The QoS comparison based decision making in [Hong06] performs a normalization procedure to compare the upper and lower bounds of the offered QoS and required QoS in three classes which are: -1, 0 and 1; respectively. The handover decision making is activated if the class of one of the upper or lower bounds is -1. In comparison, the *Analytic Hierarchy Process* (AHP) [Saat90] based handover decision making used in [Bala04, Ahme06] selects a wireless network that also satisfies application's QoS requirements. Looking at the practical validation aspect of vertical handover management approaches, it is observed that the AHP based handover decision making in [Bala06, Ahme06] is validated on the handheld mobile devices (which functions as a MBU in a mobile patient monitoring system) while the QoS comparison approaches in [Chen05,

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[30] In the experimentation, it is assumed that the GPS receiver acts as a location and time context source.

Hong06] are simulated. Hence, the NAHO mechanism uses AHP based handover decision making for the network selection.

As described in [Saat90], AHP is about dividing a problem into several sub-problems and later aggregating solutions of these sub-problems into a conclusion. Since the wireless network QoS parameters in the QoS predictions are *goodput* and *RTT*, we divided the network selection problem of satisfying biosignals delivery QoS requirements into two sub-problems as represented by the following two AHP optimization objectives: a) *Goodput objective:* Satisfy goodput requirements of the biosignals delivery; and b) *RTT objective:* Satisfy RTT requirements of the biosignals delivery. Later on, the following AHP steps are applied to make a selection of wireless network to handover to: 1) Decide the relative importance of these optimization objectives; 2) Compute the relative weight of each available network for each objective by considering the QoS requirements of the biosignals delivery; and 3) Calculate overall score for each network and select the network with the highest score for the handover.

8.1.4 Research Objective 4

The research objective 4 of this thesis is: *How to use the wireless network interfaces of the MBU to reduce its power consumption?*

In the mobile computing environment, the importance of saving the battery power of a mobile device is undisputed. The mobile communications technology requires significant power for the data transmission so that a MBU keeps connected to the wireless network [Chal99]. The battery of patient's PDA devices (e.g. QTEK9090) typically lasts for a few hours in a continuous mobile patient monitoring session [Halt04, Wac09a], whereas 24 hours battery life is expected [Kuma08]. Given that the MBU device used in the MHPMS has two wireless network interfaces (WWAN and WLAN), at a given time, only one network interface (NI) is in the ON-ACTIVE state for delivering biosignals data. From the data transmission perspective, the other NI is in the ON-IDLE state – means it is unused.

In a related work [Chen05], the vertical handover technique is combined with the strategy to selectively turning off the WLAN NI depending on the application's QoS requirements. In [Chen05] using simulations it is shown that the power savings can be achieved on a mobile device. Generally, different types of handheld mobile devices have different NI power consumption characteristics. Since in the NAHO mechanism, due to the availability of QoS predictions on the MBU, the wireless network availability is known, we decided to combine the NAHO mechanism with the strategy of selectively turning off the NIs when not in use for the data transmission. Using this strategy, we proposed two variants of the NAHO mechanism as follows: 1) $NAHO_{WLAN\text{-}OFF}$: This is the NAHO mechanism in which the WWAN NI is always powered on. However, if the WLAN NI is not in use for the biosignals transfer, then it is powered off. 2) $NAHO_{WLAN\text{-}OFF,WWAN\text{-}OFF}$: In this variant, if the WWAN (WLAN) network is selected for the biosignals delivery, then the WLAN (WWAN) NI is switched off. These NAHO variants add an extra step of POWERING-ON the unused NI if needed during the handover execution phase.

Since the NAHO mechanism uses the AHP based decision making algorithm, we added third AHP optimization objective namely – *Power savings objective: minimize power consumption of the MBU.* The relative importance of goodput objective and RTT objective was mapped to the importance of power savings objective. The network selection process is extended to consider the importance of a candidate wireless network based on the amount of power consumed to transmit data using the required NI and *current MBU battery level* of the MBU. To obtain the NI power consumption data and current battery level of the MBU, a power context source was introduced in the context-aware computing based NAHO mechanism architecture. For the power savings evaluation of the NAHO variants, the NI power consumption characteristics of two types of PDAs namely QTEK 9090 and IPAQ were obtained from [Wac09b, Barg07]. The QTEK 9090 PDA has an integrated WLAN NI, while the IPAQ device used in [Barg07] was fitted with an external WLAN card. For the QTEK 9090, in the ON-ACTIVE state, a WWAN NI consumes more power than the WLAN NI, which is the opposite case compared to the IPAQ device. The experimental results showed that using the proposed NAHO variants and QoS predictions, the power savings is observable on the mobile devices characterized by lower power consumption of the WWAN NI compared to the WLAN NI. For the mobile devices characterized by higher power consumption of the WWAN NI, no power savings is observed.

8.1.5 Research Objective 5

The research objective 5 of this thesis is: *What are the gains achieved by proposed vertical handover mechanisms and what are the corresponding overheads?*

To address the thesis problem, we proposed two context-aware vertical handover mechanisms namely *mobile controlled handover* (MCHO) mechanism and *network assisted handover* (NAHO) mechanism. In the MCHO mechanism, the handover decision is taken based on the context information available locally on the MBU, while in the NAHO mechanism, the handover decision making also uses context information obtained from the fixed network – which is *QoS predictions*. Both of these handover mechanisms select a wireless network from the set of available wireless networks for delivering biosignals. The QoS experienced by the patient monitoring service is known as *extra-BAN communication QoS*. The vertical handover functionality is newly introduced in the MHPMS. Also, for assessing the possibility of power savings, the NAHO mechanism was combined with the strategy to selectively turn off the unused network interface (NI) of the MBU. In order to quantify respective gains/overheads, we proposed metrics to quantify the following: *wireless network performance* (in terms of *biosignals delivery goodput* and *RTT*), *vertical handover performance* (in terms of *handover triggering delay*, *handover execution delay* and *total handover delay*) and *power savings performance* (in terms of *remaining energy level* and *estimated depletion time*). These metrics are derived from the review of related literature [Bern04, Chal99, Kass08] and peer experience in the MHPMS development [Alon02, Halt04, Wac09a].

Depending on the availability of context sources providing information necessary for handover decision making, the handover experiments reported in this thesis fall into two categories: *using an operational MHPMS system test bed* and *using simulations*. There is no involvement of the patients in these experiments. The performance evaluation of the MCHO mechanism is conducted using a real-operational MHPMS test bed that provides three types of Internet connectivity to the MBU, using a GPRS network, 802.11b network and fixed network connectivity via USB port. This performance evaluation was conducted for two types of biosignals delivery requirements (cardio biosignals profile – goodput requirements: *28472 bps* and RTT requirements: *500 ms* and generic monitoring biosignals profile – goodput requirements: *40554 bps* and RTT requirements: *500 ms*). The experimental results of the MCHO mechanism conclude that the currently deployed communication infrastructure is inadequate to specially support the RTT requirements of the mobile patient monitoring applications.

The NAHO mechanism makes use of QoS predictions to take a handover decision. Due to the unavailability of operational QoS predictions context source, the NAHO mechanism is evaluated using an extensive set of simulations, whereas the patient is assumed to travel distance of 8.470 km between the geographic coordinates of source location and destination location at the speed of 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 90 and 100 km/h respectively. The performance of the NAHO mechanism was compared with the MCHO mechanism. The experimental results showed that compared to the MCHO mechanism the NAHO mechanism provides 18% higher goodput and 7.6% lower RTT for the biosignals delivery at the cost of 23.3% higher number of handovers. The performance improvement of the NAHO mechanism is attributed to the AHP based network selection technique and availability of context sources providing QoS predictions.

The simulation experiments to analyze power savings potential of the NAHO mechanism and NAHO variants used NI power consumption data of two devices: QTEK 9090 and IPAQ. The simulation results show that it is possible to achieve power savings for the devices in which the WLAN NI consumes higher power compared to the WWAN NI (e.g. IPAQ). In contrast, for the MBU in which the WWAN NI consumes higher power than the WLAN NI, no power savings could be achieved (e.g. QTEK 9090). The AHP optimization objective-wise performance results show that on the QTEK 9090 device, the increase in the power savings preference value neither achieves any power savings nor affects the performance of goodput objective and RTT objective. In comparison, on the IPAQ device, increasing the importance of power savings objective has a positive effect on the power savings performance at the cost of lower goodput performance and RTT performance. In summary, the proposed AHP based QoS-aware and power-aware network selection mechanism is found to be a suitable decision making technique to address the aspects of patient mobility and improve extra-BAN communication QoS in the mobile patient monitoring system.

8.2 General Conclusions

The vision of *Pervasive Healthcare* outlined in [Vars07] aims at providing healthcare to anyone, anytime, and anywhere by removing geographical, temporal and other limitations while increasing both the coverage and quality (of the pervasive healthcare systems). As a step to realize this vision, in this thesis we proposed two context-aware vertical handover mechanisms for use in the *MobiHealth Patient Monitoring System* (MHPMS). Thee mechanisms are *mobile controlled handover (MCHO) mechanism* and *network assisted handover (NAHO) mechanism*. These handover mechanisms are intended to handle wireless network connectivity problems arising from the patient mobility and provide sufficient *extra-BAN communication QoS* for continuous and real-time delivery of patient's biosignals to the computing device of the healthcare professional.

Both of the proposed mechanisms incorporate following important requirements which are in alignment with the vision of pervasive healthcare: While the patient monitoring session is in progress, the handover mechanisms are able to detect network availability changes and initiate handover decision making process as a response to the situations in which the patient moves out of the coverage area of wireless network or the availability of a new wireless network that may offer better QoS is detected. In addition to this, to increase the duration of mobile patient monitoring between two subsequent battery recharges a power savings feature that selectively switches off unused network interfaces of the MBU is provisioned in the NAHO mechanism. By incorporating these features, the proposed mechanisms address the research problem in the sense that we show how the context-aware computing paradigm [Schi94, Dey01] and vertical handover management process [Kass08] can be used in cohesion to enable new and useful functionalities in a mobile patient monitoring system.

We do not imply that the only solution to the research problem must be in terms of the vertical handover mechanisms. E.g. by incorporating all the steps of biosignals processing (which are *data acquisition*, *signal processing*, *sensor fusion*, *feature extraction* and *decision making*) within the patient's BAN locally, the need for delivering patient's biosignals to the back-end system can be minimized (e.g. MHPMS application in the *myofeedback system* [Veld08]) which reduces the amount of biosignals to be delivered to the back-end system and thus reduces power consumption of the MBU network interfaces. However, the current state of the art shows that this application scenario is not applicable to all the healthcare applications. E.g. in the MHPMS application case of *trauma patient monitoring* [Alon02], it is a mandatory requirement that the patient's biosignals be delivered continuously to the hospital, so that the decision about prospective surgery can be taken. In these type of mobile patient monitoring cases, we have been able to demonstrate qualitatively and quantitatively the benefits of incorporating vertical handover mechanisms to address the research problem.

Because of the appliance of context-aware computing paradigm [Dey01, Schi94] in the mobile patient monitoring domain as recommended in the vision on pervasive computing [Vars07] and in the AWARENESS project [Wegd05, Broe08, Pedd09, Wac09b, Mei10] further benefits can be achieved by extending the proposed NAHO mechanism. Since the proposed mechanisms are independent of the current wireless technologies and whenever *QoS Information Service* (QoSIS) [Wac06, Wac08, Wac09b] provides a complete set of wireless network QoS predictions (including both *goodput* and *RTT* QoS parameters) along the user mobility path, the merits of the proposed NAHO mechanism may be realized in the MHPMS to alleviate the wireless network connectivity problems and limited MBU battery power problems observed during the trials of MHPMS [Alon02, Halt04]. However, to realize the full benefits of the NAHO mechanism, it is expected that the accurate indoor [Liu07] and outdoor location detection techniques [Djunk01] are in place to provide patient's location in terms of the geographic coordinates.

From the study of multiple mobile patient monitoring systems [Ango00, Gao07, Gay07, Halt04, Lin04, Sata00 and Wai08] and also as confirmed from the recent ubiquitous computing survey in the healthcare domain [Kuma08], it is common for the current mobile patient monitoring prototypes to suffer from the unpredictable wireless connectivity and bandwidth problems. The observed RTT problems are even more serious as the WWAN wireless network (GPRS) used in the conducted MCHO mechanism experiments was not able to satisfy the RTT requirements of continuous mobile patient monitoring cases. Hence we think that if a reliable QoS information service is put in practice, the upcoming mobile patient monitoring systems will also benefit from the research reported in this thesis.

8.3 Future Work

In this section, we discuss the topics for future work as follows: 1) Practical deployment of the NAHO mechanism; 2) QoS in the mobile patient monitoring domain.

8.3.1 Practical Deployment of NAHO Mechanism

The simulation results are encouraging to deploy the NAHO mechanism in an operational MHPMS. However, there are a number of concerns involved in such practical implementation. Herewith we elaborate on these concerns and provide pointers to solve address these.

QoS Predictions Context Information

In the NAHO mechanism, the context processor hosted on the MBU requests QoS predictions as the need arises. In these cases, the QoS predictions are *pulled on-demand*. Other strategies which need to be investigated for requesting QoS predictions are:

1) In the wireless network area characterized by lower goodput and higher RTT properties, receiving QoS predictions on the MBU may take longer time. In the situations where a user is moving at high speed, the QoS predictions would reach the MBU after the user has left the area. These types of cases can be envisioned early on by monitoring the speed of the MBU. If the user movements can be predicted using approaches such as those described in [Erba01], the QoS predictions for the future patient locations can be sent early on to solve this problem.
2) The WLAN technologies are characterized by higher data rate and lower delay compared to WWAN technologies. Hence, it may be possible to download a map of QoS predictions while the MBU is connected to the WLAN network.

In the simulation experiments, it is assumed that the user moves at a constant speed. However, in reality, the user speed varies because of factors such as traffic, curves and obstacles on the street. Hence in the NAHO mechanism, further, it would be useful to incorporate a *moving average function* to reliably determine average user speed. The simulation of QoS predictions used in the experiments assumes that the wireless network has a circular coverage area. However, in reality, the wireless network does not always provide a circular coverage. To simulate irregular coverage areas, data structures such as *Quad trees* [Same80] and *chain codes* [Kane85] proposed in the area of *computer graphics* need to be researched.

The *prediction generator module* in the *QoS predictions CS simulator* assigns bandwidth values to simulated QoS predictions from the following range: *10000 bps – 25000 bps* for a GPRS network, and *10000 bps to 55000 bps* for a WLAN network. Similarly, the delay values are selected from the following range: *1000 milli-seconds to 25000 milli-seconds* for a GPRS network, and 35 milli-seconds to 1000 milli-seconds for a WLAN network. These ranges are obtained from handover experiments conducted for the MCHO mechanism. Herewith, we propose to study historic wireless network QoS data collected by the *QoSIS* [Wac09b] to analyze the relationship between spatiotemporal context information and wireless network QoS. The following is a list of spatiotemporal parameters: *day of week*, *time*, *location*, *wireless network operator*, *receiver signal strength* and *MBU battery level*. These parameters are used in QoSIS to categorize historic wireless network QoS usage data. The results of this study can be used in the predictions generator for assigning more realistic QoS values in time dimension.

In certain conditions, QoS predictions may not be available. E.g., there is not enough historic data available at the QoSIS to generate predictions or the QoSIS itself is offline. In these situations also, it is possible to benefit from the handover functionality that uses the proposed MCHO mechanism.

Vertical Handover Execution Process

The simulation experiments of the NAHO mechanism consider that all the WLAN networks are unsecured i.e. they implement open system authentication. However, in practice, usually the WLAN networks are secured. The mobile device access control to the WLAN base stations is implemented at different layers using a variety of mechanisms [Ott05]. E.g., at the IEEE 802.11 MAC layer there are mechanisms such as *pre-shared key* (WEP) *authentication* or *IEEE 802.11i* authentication. Certain wireless network operators use web-based *Universal Access Method* (UAM) for the authentication. The automated 802.11 authentication experiments conducted in [Ott05] for 14 base stations show that the time required for authentication varies from 0.2 seconds to 13 seconds with an average duration of 3.19 seconds. The vertical handover execution process needs to take into account whether the MBU has necessary permissions to use the WLAN network and time required for authentication.

Large Scale Deployment Concerns

The mobile patient monitoring applications are aimed towards a mass segment of population e.g. elderly population. In the scenarios of large scale deployment of mobile patient monitoring systems (e.g. multi-storey nursing home), there is a possible high concentration of patients which are being followed by a patient monitoring system simultaneously. For the WWAN networks, this involves technical situations where available wireless link bandwidth is shared between multiple MBUs which simultaneously transmit patient's biosignals. According to [Lind02], there is a limit on the maximum number of GPRS users that can be managed simultaneously by a GPRS cell without QoS degradation. The performance analysis of 802.x networks conducted in [Xiao02] shows that when the number of simultaneously transmitting mobile devices increases, overall maximum throughput of a network (i.e. *saturation throughput*) decreases. A performance anomaly for 802.x networks noticed in [Heus03] is that when a mobile device is far away from the wireless access point, it is subject to signal fading and interference. In such cases, a mobile device uses a lower bit rate than the others, which results in the performance degradation of other mobile devices. In the cases where such situations occur spontaneously (without any existing pattern), the extra-BAN communication QoS experienced by the MBU may not necessarily match with the QoS values received in the QoS predictions. The WWAN performance tests conducted during the MHPMS trial indicated degradation in the QoS performance while ten MBUs located in the same room simultaneously transmitted data over the WWAN network. A challenge in this situation is how to sense these environmental aspects in real-time – e.g. number of MBUs simultaneously transmitting biosignals, the predicted QoS and the actual QoS and adapt biosignals transmission such that the available network resources can be optimally used.

In certain sense, this problem is analogous to the mobile patient monitoring resources demand and supply mismatch problem investigated in [Mei10]. Therein, the mobile patient monitoring tasks are composed of multiple *biosignals processing units* (BSPU) while every BSPU has associated resources requirements in terms of required computing power, required network resources and required battery power. An ordered set of BSPUs is required to support continuous mobile patient monitoring. A problem investigated in [Mei10] is how to dynamically assess the current state of available communication and computation resources and assign these resources dynamically to an ordered set of BSPUs so that the gap between resources demand and supply can be minimized. The solution proposed to this problem in [Mei10] is a middleware named MADE (*Monitoring, Analysis, Decision, and Enforcement*). Since a set of available wireless networks is a communication resource, the handover management process of the NAHO mechanism can be executed in the back-end system which has knowledge of both, QoS predictions and realized biosignals delivery QoS. This process will monitor and analyze the current state of communication resources, the number of MBUs transmitting biosignals data, QoS requirements for each individual mobile patient monitoring session and perform assignment of wireless networks to the MBUs dynamically. This assignment need to be further communicated with the MBU, so that the MBU uses the wireless network recommended by the back-end system.

8.3.2 QoS in Mobile Patient Monitoring Domain

In recent years, the *European Union* (EU) and the *Dutch Government* have invested heavily in the healthcare sector and sponsored several research projects related to mobile patient monitoring. The trend mentioned herein is also applicable to other developed countries such as Singapore, Australia, United Kingdom, Canada and United States of America. The target population which will be benefited by these projects is a mass segment of the population. An example of such project is the BRAVEHEALTH project funded under the *European Commission Seventh Framework Programme* (FP7)[31] program. The BRAVEHEALTH project is targeted at an integrated, adaptive, context-aware remote diagnosis and management of cardiovascular diseases.

Compared to the mobile devices used in this research, the present day handheld mobile devices[32] are equipped with higher amount of processing power, better form factor, integrated synchronous and asynchronous communication facilities, location and activity detection technologies, practically unlimited memory, better application processing capabilities, abilities to communicate with other sensor devices in the surroundings and integrated network interfaces to connect to multiple types of managed mobile and ad-hoc wireless networks (e.g. GPRS, EDGE, HSDPA, WLAN, Bluetooth). The Internet bandwidth availability has increased. The healthcare applications are undergoing innovations, again due to the changing role of ICT in the human life. E.g. in the current generation of healthcare projects, it is expected that

[31] European Commission – Seventh Framework Programme (FP7) homepage http://cordis.europa.eu/fp7/home_en.html

[32] E.g. Apple iPhone 4, Samsung i9000 Galaxy S

along with the biosignals monitoring and delivery, the patient's MBU will also handle data traffic originating from the healthcare mobile virtual communities [Eyse4, Beij09]. As a result, from the data transfer perspective, the MBU will handle healthcare application data characterized by mixed QoS requirements [Skor10]. The QoS requirements of healthcare applications are dependent on the application purpose and application area. In the vision of pervasive healthcare [Vars07], it is recommended that the healthcare related QoS requirements be specified in terms of the *Healthcare Quality of Service* (H-QoS) as the following.

1. *Patient-centric H-QoS* are reliability of message delivery and monitoring delay.
2. *Network-centric H-QoS* are message throughput and number of patients supported.
3. *Healthcare professional-centric H-QoS* are cognitive load of healthcare professionals and the number of correct medical decisions.

In align with this discussion; the work reported in this thesis can be extended in the following ways:

- The QoS requirements elicitation methodology proposed herein can be extended to quantify mobile patient monitoring data QoS requirements in terms of the above H-QoS indices.
- The optimization objectives of the AHP decision making algorithm can be extended to select a wireless network that provides optimal QoS experience in terms of the H-QoS satisfaction.

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Appendix A: Selected Mobile Computing Terms

- *Mobile Network Operator* (MNO)*:* A mobile network operator is a business organization which owns the radio frequency spectrum and has its own cellular network infrastructure for providing voice and/or data services to the mobile users. E.g. *Vodafone*.
- *Wireless Wide Area Network (WWAN):* A wireless network spanning over a large geographic area (e.g. entire city) and typically made available by the MNO for the purpose of data transfer to and from the mobile device. Some examples of WWAN technologies are GPRS, UMTS and HSDPA. A WWAN could also be provided by a satellite system.
- *Wireless Local Area Network (WLAN):* As compared to WWAN, the WLAN spans over a smaller geographic area (e.g. home) and could be installed very easily by an individual. WiFi is a popular WLAN technology.
- *Internet:* The Internet is a global network of interconnected computers which enables its users to share information among each other based on the Internet Protocol Suite.
- *Internet Service Provider (ISP):* An Internet service provider is a company that provides Internet access to its customers using a data transmission technology appropriate for delivering Internet Protocol datagrams, such as dial-up, DSL, cable modem or dedicated high-speed interconnects.
- *Wireless Internet Service Provider (wireless ISP):* The Wireless ISP is an ISP providing Internet access (to the mobile devices) using WWAN or WLAN technologies. Thus, apart from the organizations which provide WWAN and WLAN Internet access, we also consider the individuals like the owners of the cafes, restaurants

and even household residents as wireless ISPs which have WLAN infrastructure in place to provide Internet access.

- *Wireless ISP Network*: The WWAN or WLAN network used by the wireless ISP for providing Internet access to the mobile devices.
- *Network Interface Card* (NIC): NIC is a hardware component of the computing devices designed to allow them to communicate over a network of other computing devices.
- *Wireless Network Interface Card (wireless NIC):* A wireless NIC is a hardware component designed to allow a computing device to connect to a wireless network. These could be integrated into the device chipset or could be attached externally say using USB port to provide wireless access to the device. A wireless NIC must have an associated IP address so that the associated computing device can participate in the Internet.
- *Handheld mobile device or Handhelds:* A pocket-sized computing device such as cellphone, smartphone or PDA typically has a display screen with touch input and/or a miniature keyboard. The other mobile devices such as notebook PC or ultra-mobile PC are considered as mobile devices but not as handhelds because of their higher form factor. Nowadays, the handhelds often are equipped with at least one WWAN NIC and one WLAN NIC.

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Acronyms

Acronym	Meaning
3GPP	3rd Generation Partnership Project
AAO	Active Application Oriented
ABC	Always Best Connected
AES	Advanced Encryption Standard
AfA	Adaptation for Application
AHP	Analytic Hierarchy Process
AID-N	Advanced Health and Disaster Aid Network
API	Application Programming Interface
APIPA	Automatic Private IP Addressing
AUX	Auxiliary
AWARENESS	Context AWARE mobile Networks and ServiceS
BAN	Body Area Network
BER	Bit Error Rate
BESys	Back-End System
CCS	Communication Context Source
CDMA	Code Division Multiple Access
CIR	Carrier-to-Interferences Ratio
CMS	Continence Management System
CP	Context Processor
CPU	Central Processing Unit
CR	Context Reasoner
CS	Context Source
DHCP	Dynamic Host Configuration Protocol
DNC	Domain Name Cluster
DNS	Domain Name System
DS	Device Service
DSL	Digital Subscriber Line
E3	Everest Extreme Expedition
ECA	Event-Condition-Action
ECG	ElectroCardioGram
EEG	ElectroEncephaloGram
E-Health	Electronic Health
EPR	Electronic Patient Records
EVDO	EVolution Data Optimized
FFT	Fast Fourier Transform
FP7	European Commission Seventh Framework Programme
GPRS	General Packet Radio Service
GPS	Global Positioning System

GRA	Grey Relational Analysis
GSM	Global System for Mobile Communications
GSR	Galvanic Skin Response
GUI	Graphical User Interface
HRV	Heart Rate Variability
HSDPA	High-Speed Downlink Packet Access
HTTP	HyperText Transfer Protocol
ICT	Information and Communication Technology
H-QoS	Healthcare Quality of Service
ICU	Intensive Care Unit
ID	Identifier
IO	Input Output
IP	Internet Protocol
ISP	Internet Service Provider
J2ME	Java 2 Platform Micro Edition
JMF	Java Media Framework
JNI	Java Native Interface
JVM	Java Virtual Machine
KML	Keyhole Markup Language
LED	Light Emitting Diode
LEOS	Low Earth-Orbiting Satellites
LNCD	Light Network Capability Discovery
LSS	Location Service Server
LSTM	Light Session Transfer Module
MADE	Monitoring, Analysis, Decision, and Enforcement
MADM	Multi-Attribute Decision Making
MAHO	Mobile Assisted HandOver
MBU	Mobile Base Unit
MCHO	Mobile Controlled HandOver
MEG	MagnetoEncephaloGram
MEW	Mulplicative Exponent Weighting
M-Health	Mobile Health
MHPMS	MobiHealth Patient Monitoring System
MIH	Media Independent Handover
MIHF	Media Independent Handover Function
MIHO	Mobile Initiated HandOver
MIIS	Media Independent Information Server
MNO	Mobile Network Operator
MSP	Mobile Service Platform
NAHO	Network Assisted HandOver
NAL	Network Abstraction Layer
NAT	Network Address Translation
NCHO	Network Controlled HandOver
NI	Network Interface
NIC	Network Interface Card
NMS	Nomadic Mobile Service

NRM	Network Resource Model
NTP	Network Time Protocol
OS	operating System
OSGi	Open Services Gateway initiative
PC	Personal Computer
PDA	Personal Digital Assistant
PHM	Personalized Health Monitoring
PPG	PhotoPlethysmoGraph
QoS	Quality of Service
QoSIS	Quality of Service Information System
QoSCS	QoS Predictions Context Source
RA	Rheumatoid Arthritis
RF	Radio Frequency
RMI	Remote Method Invocation
RSS	Received Signal Strength
RTT	Round Trip Time
SAP	Service Access Point
SAW	Simple Additive Weighting
SDIO	Secure Digital Input Output
SEMG	Surface ElectroMyoGraphy
SFE	Sensor Front End
SIR	Signal-to-Interferences Ratio
SMAC	Shared Medium Access Control
SOA	Service Oriented Architecture
SOC	Service Oriented Computing
SSID	Service Set Identifier
TCP	Transmission Control Protocol
TFFST	Finite-State Transducer with Tautness Functions and identities
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
UAM	Universal Access Method
UMTS	Universal Mobile Telecommunications System
UPnP	Universal Plug and Play
URL	Uniform Resource Locator
USB	Universal Serial Bus
WLAN	Wireless Local Area Network
WNP	Wireless Network Provider
WPU	Wearable Processing Unit
WWAN	Wireless Wide Area Network
XML	Extensible Markup Language

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