

MobiHealth: Ambulant Patient Monitoring Over Next Generation Public Wireless Networks

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Abstract. The wide availability of high bandwidth public wireless networks as well as the miniaturisation of medical sensors and network access hardware allows the development of advanced ambulant patient monitoring systems. The MobiHealth project developed a complete system and service that allows the continuous monitoring of vital signals and their transmission to the health care institutes in real time using GPRS and UMTS networks. The MobiHealth system is based on the concept of a Body Area Network (BAN) allowing high personalization of the monitored signals and thus adaptation to different classes of patients. The system and service has been trialed in four European countries and for different patient cases. First results confirm the usefulness of the system and the advantages it offers to patients and medical personnel.

1 Introduction

In the next few years the expansion and availability of high bandwidth wireless networks, like GPRS and UMTS, combined with the ever-advancing miniaturization of sensor devices and computers, will give rise to new services and applications that will affect and change the daily life of citizens. An area where these new technological advances will have a major effect is health care. Citizens, being patients or non-patients, will not only be able to get medical advice from a distance but will also be able to send from any location full, detailed and accurate vital signal measurements, as if they had been taken in a medical center, implementing what we can call “ubiquitous medical care”.

Towards this direction different initiatives, projects and prototypes were developed in the past few years ranging from stand-alone devices measuring and storing one specific vital sign (like insulin level) to chest bands measuring heart and blood parameters and easy to wear t-shirts with woven sensors. However all these devices are not linked with any specific service and do not provide sufficient flexibility for personalization. The device collects the vital signal data and brings to the medical expert for post-processing; no direct, on-line connection being available. On the other hand the devices that do transmit the vital signal measurements, only transmit a fixed small number of vital signals (one or two) without any possibility for expansion. Furthermore, these devices cannot be personalized, by adding for example a specialized sensor for a specific patient.

The MobiHealth project's target was to provide a solution that does not suffer from the above limitations. The project, started in May 2002 and completed in February 2004, has indeed developed a system and a service for ambulant patient monitoring over public wireless networks. Based on a body area network interconnecting different vital signal sensors and actuators, the measurements are transmitted using UMTS[1] (or GPRS) to the health care center where they are presented live to the medical personnel. This way patients can be continuously monitored and receive advice when needed. In the last months of the project 9 different trials scenarios were implemented for different types of patients. These trials allowed us to identify problems and issues in the development of mobile e-health services and identify limitations and shortcomings of the existing and forthcoming public network infrastructure.

The use of GPRS and UMTS as communication technology is essential due to the need to support a continuous connection to the healthcare center, the high bandwidth required for the transmission of the data (which can easily reach the level of 100 Kbps), the communication costs involved (in GPRS and UMTS, the cost is calculated per Kb, instead of per minute of connection) and the high quality of service required for all health related applications. These are requirements that cannot be met with current GSM technology. In fact the overall goal of MobiHealth was to evaluate the ability of 2.5 and 3G communication technologies to support innovative mobile health services. The main output of the project therefore is an assessment of the suitability of GPRS and UMTS to support such services. In addition the project delivered an architecture for, and a prototype of, a health BAN and a generic m-health service platform for provision of ubiquitous healthcare services based on Body Area Networks.

In this paper we present the developed MobiHealth system and service, give an overview of the trials performed and discuss the issues and limitations related to the deployment of 2.5/3G networks in the support of mobile health care services. Section 2 presents an overview of the different systems available today, discussing briefly their advantages and disadvantages, section 3 presents an overview of the MobiHealth architecture while section 4 describes the performed trials. Finally section 5 presents the evaluation methodology and the first results of the trials' evaluation and section 6 our conclusions and future directions.

2 Issues Related to Mobile Health Care Monitoring Systems

The need for a cost reduction in health care expenses as well as the demand from patients for ubiquitous health care provision (health care available anywhere at any time) boosted the research and the development of different types of wearable and mobile health care systems and devices. While simple vital signal measuring devices, like for example chest band for training and portable glucose control devices, have been available in the market for many years, it is only during the last few years that wearable and mobile sensors became sufficiently advanced, diverse and low cost, able to provide measurement in a quality comparable to laboratory measurements. Combined with the miniaturization of computers and communications hardware different wearable health care devices were developed and some are already available in the market.

The systems available today in the market or under development can be classified in different ways, depending on their capabilities and target use. A first element is the number of vital signal sensors that are or can be supported by the device/system. At the lower end we find specialized devices measuring only one signal, like glucose or heart rate, like the Glucowatch of Sankyo Pharma and Cygnus [2] measuring the glucose level for diabetics. In the middle we

have closed systems that are able to measure a predefined set of vital signals, like the *lifeshirt* of Vivometrics [3] and VTAM from Medes [4], while at the high end we have devices that are configurable allowing the integration of an arbitrary number of sensors, like the MobiHealth system [5].

The second element to consider in a classification is the handling of the measurement data. We have from one side devices that collect the measurement data, store them locally and the user must transfer the collected measurements off-line to the health broker where they are post-processed. An important aspect is the quantity of data that can be stored, expressed in minutes or hours of measurements. On the other side we have devices and systems that transmit the data on-line, using a wireless connection, to the health broker. The important issues are the capacity (bandwidth available) of the network and the coverage area (short range in-house or use of public wireless networks).

A third element is the simplicity of use and wearability of the sensors. We have systems where the sensors are integrated in a T-shirt or a wrist watch-like device, systems where the sensors are independent devices linked wirelessly or wired to a small processing device and implantable sensors that are permanently attached to the patient.

Other issues that define the usability and functionality of an ambulant monitoring system are its autonomy, the accuracy of the measurements and the integrated medical analysis. The system autonomy depends on its power consumption (which is high for systems that transmit data using a wireless connection), while the accuracy of measurement depends on the type of sensors used (for example dry ECG sensors versus “standard” ones) and the algorithms that eliminate artefacts due to movement of the user.

3 The MobiHealth System

The MobiHealth system provides a complete end-to-end e-health platform for ambulant patient monitoring, deployed over UMTS and GPRS networks. The MobiHealth patient/user is equipped with different vital constant sensors, like blood pressure, pulse rate and ECG interconnected via the *healthcare Body Area Network* (BAN). The *Mobile Base Unit* (MBU) is the central point of the healthcare BAN, aggregating the vital sensor measurements and transmitting them via UMTS or GPRS to the back-end system, which can be located within the health broker premises or be part of a wireless service provider. From there the measurements are dispatched to the health care broker where the medical personnel monitor them. It must be noted that automated monitoring and patient feedback is currently not supported by the MobiHealth system, as this was outside the scope of the project.

3.1 The Healthcare BAN architecture

The concept of the Body Area Network originally came from IBM[6] and was developed further by many other researchers, for example at Philips [7], at the University of Twente [8], and at Fraunhofer [9]. In the Wireless World Research Forum’s *Book of Visions*, we define a BAN as “*a collection of (inter) communicating devices which are worn on the body, providing an integrated set of personalised services to the user*”[10]. In the context of the MobiHealth project the *Healthcare BAN* is a health monitoring tool that consists of sensors, actuators, communication and processing facilities connected via a wireless network which is worn on the body and which moves around with the person (i.e., the BAN is the unit of roaming).

We call communication between entities within a BAN *intra-BAN communication*. To allow external communication of the BAN for remote monitoring we use a gateway, the Mobile Base Unit (MBU), which provides the *extra-BAN communication*. Figure 1 shows the architecture of a healthcare BAN. Sensors and actuators establish an ad-hoc network and use the MBU to communicate outside the BAN. The MBU could also be implemented as a sensor or actuator that provides extra-BAN communication services.

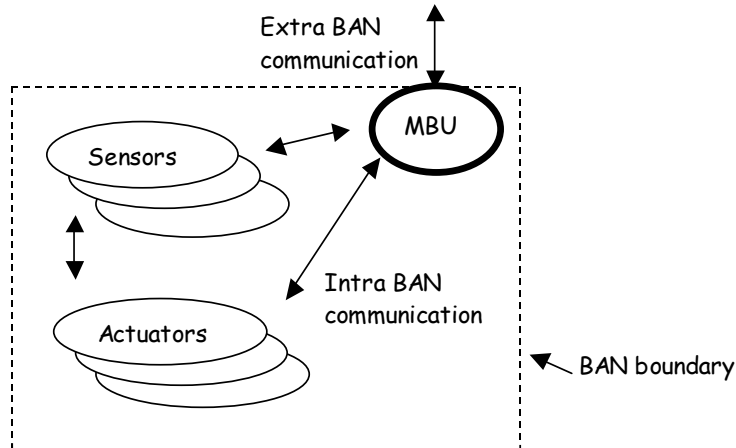


Figure 1 Healthcare BAN architecture

Intra-BAN communication is based on wireless networks like Bluetooth[11] and Zigbee[12], while the extra-BAN communications is done via GPRS and UMTS.¹

A sensor is responsible for the data acquisition process, ensuring that a physical phenomenon, such as patient movement, muscle activity or blood flow, is first converted to an electrical signal, which is then amplified, conditioned, digitised and communicated within the BAN.

The Healthcare BAN sensors can be self-supporting and/or front-end supported. Self-supporting sensors have a power supply and facilities for amplification, conditioning, digitisation and communication. Self-supporting sensors are independent building blocks of a BAN and ensure a highly configurable healthcare BAN. However, each sensor runs at its own internal clock and may have a different sample frequency. Consequently, mechanisms for the synchronization between sensors may be needed.

Front-end supported sensors share a common power supply and data acquisition facilities. Consequently, front-end supported sensors typically operate on the same front-end clock and jointly provide multiplexed sensor samples as a single data block. This avoids the need for synchronization between sensors.

3.2 Service platform architecture

Collecting and transmitting the vital signal measurements is only part of the healthcare service developed in the MobiHealth project. The Healthcare BAN is only one part of a service platform that integrates the mobile part (healthcare BAN) and the health broker resident system. Figure 2 shows the overall functional architecture of the MobiHealth service platform. The dotted square boxes indicate the physical location where parts of the service platform are

¹ WLAN was also used in the initial stages of the project for testing purposes.

executing. The rounded boxes represent the functional layers of the architecture. The M-health service platform consists of sensor and actuator services, intra-BAN and extra-BAN communication providers and an M-health service layer. The intra-BAN and extra-BAN communication providers represent the communication services offered by intra-BAN communication networks (e.g. Bluetooth) and extra-BAN communication networks (e.g. UMTS), respectively. The M-health service layer integrates and adds value to the intra-BAN and extra-BAN communication providers. The M-health service layer masks applications from specific characteristics of the underlying communication providers, such as the inverted consumer-producer roles.

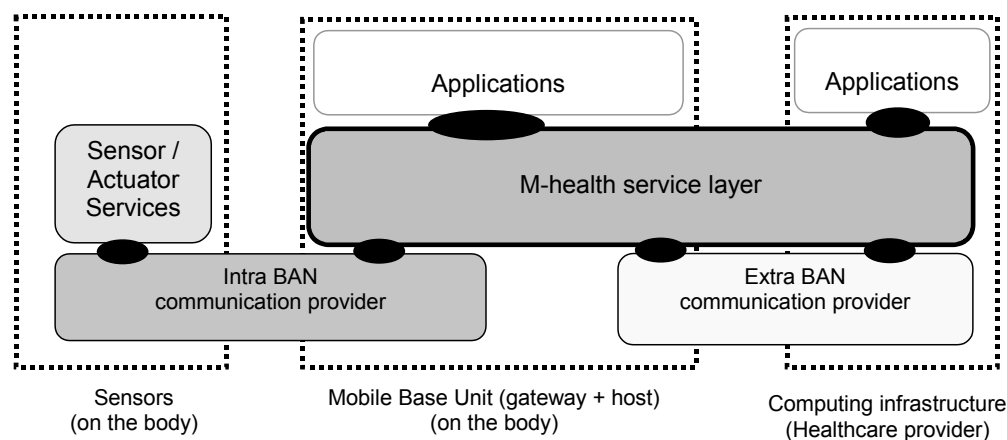


Figure 2 Service platform functional architecture

Applications that run on top of the service platform can either be deployed on the MBU (for on-site use e.g. by a visiting nurse) or on the servers or workstations of the healthcare provider, i.e. the call centre or the co-located secondary care centre in Figure 2. For this the M-health service platform offers a number of services including:

- *BAN registration*: the service platform maintains a list of active BANs and allows applications to retrieve the specific configuration of a BAN.
- *BAN discovery*: applications can subscribe to the platform to receive a notification in case a BAN becomes active (i.e. a patient switches on a BAN).
- *BAN authorization and authentication*: the service platform authenticates BANs and only allows authorized BANs to convey data.
- *BAN data encryption*: the platform encrypts data that is conveyed over unsecured networks
- *BAN configuration*: the service platform allows online configuration and management of the BANs, such as (de)activation of specific sensors or modification of the sample frequency of a sensor.
- *Data acquisition control*: the service platform enables applications to start, stop or temporarily interrupt the data acquisition process of a BAN.
- *Query and modify actuator status*: applications can manipulate actuators from a distance.
- *BAN data storage*: the service platform can act as an intermediate storage provider to applications. Applications determine the minimal duration of the storage.
- *BAN data monitoring*: the service platform can apply filtering algorithms on the BAN data to determine if an interesting event has taken place (e.g. a patient has dropped on the floor) and report this event to the application layer.

A refined view of the M-Health service layer is shown in Figure 3 for the case where the M-health service platform user (e.g. at a hospital) is located remotely from the call centre. The arrows in the figure show the flow of the BAN data. The BANip entity is a protocol entity for the BAN interconnect protocol [13]. Peer entities can be found on the MBU and on the computing infrastructure (in the ‘fixed’ network). The BANip entities communicate through a proxy, that authenticates and authorizes the BANs’ connection.

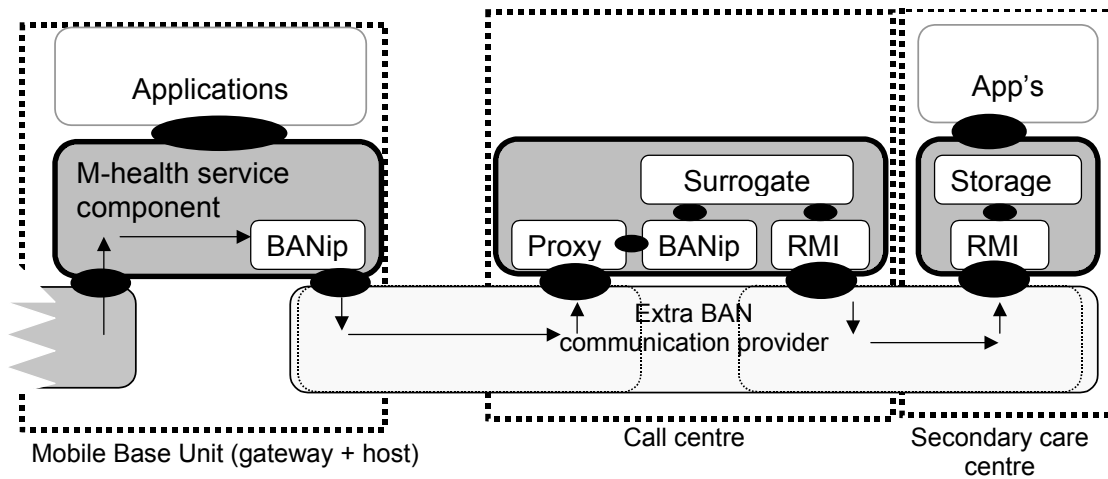


Figure 3 Refined view of the service platform

The surrogate component uses the BANip protocol to obtain BAN data. This component contains a representation of the BAN (i.e. the surrogate) and shields other components in the ‘fixed’ network from the BANip and direct interaction with the BAN. The surrogate component can be accessed by any application protocol, including Remote Method Invocation (RMI) as depicted in Figure 3. The storage entity uses RMI to interact with the surrogate as if it interacts with the remote BAN at the location of the patient, without the burden of the discovery, registration and authentication of the BANs. The surrogate component is therefore the intermediary whereto BAN data from the location of the patient is pushed and wherefrom the data is pulled by the application component residing at the secondary care centre. The storage entity provides the BAN data storage service to the application layer. Configuration, discovery and monitoring services are offered as separate entities, with the same structure as the storage entity.

Applications that use the m-health service layer can range from simple viewer applications that provide a graphical display of the BAN data, to complicated applications that analyse the data.

3.3 Service platform technical requirements

To leverage the healthcare BAN for use as a *remote* monitoring tool several issues and considerations were taken into account in the design and development of the supporting healthcare service platform. These issues reflect both commercial and social needs or restrictions, as well as technical limitations of underlying infrastructures [16]. The most important ones being *scalability*, *security* and *extra-BAN network restrictions*.

The healthcare service platform must be able to support services that cover niche healthcare cases that require the simultaneous monitoring of small numbers of patients (e.g., ranging from 10 to 100 BANs) to large-scale chronic disease management processes (e.g., 100,000+ BANs used to monitor COPD patients). In addition geographical scalability, that is global coverage, should be supported.

The healthcare service platform connects the BAN with the Internet. Consequently, the BAN is subject to attacks from malicious Internet users who either try to break into the system or frustrate its use. Therefore the healthcare service platform should be protected from attacks like Denial of Service (DoS). Mechanisms that ensure data integrity must be included to prevent corruption of BAN data. Each BAN should authenticate itself with the service platform, which should only allow authorized BANs to send BAN data.

Traditionally, providers of data (such as web servers) are deployed on a computing infrastructure with sufficient network and processing capacity. Consumers of data (such as web browsers) assume that providers are available most of the time (except for maintenance) and have sufficient bandwidth to serve a reasonable amount of consumers. This model was the one adopted by the public wireless network operators where the data consumer, i.e., the mobile device, initiates a network connection to the producer. Based on this assumption, most network operators of 2.5/3G networks hand out private space IP addresses to mobile devices. Connection establishment initiated from a fixed host on the public Internet to a mobile device is therefore inhibited.

However in the MobiHealth system each BAN *is a data producer*. For the service platform, the producer and consumer roles are thus inverted because the provider of data is deployed on a mobile device (i.e. the MBU) while the consumer of data is deployed on a fixed host with sufficient processing and communication capacity. The MBU may be temporary unavailable, due to the short life-time of batteries or because it has moved to an area without coverage of the public wireless infrastructure. The service platform therefore masks the inversion of the producer-consumer roles from the BAN and the end-users (e.g., a patient wearing the BAN or a medical specialist analyzing the BAN data).

3.4 Implementation details

The Healthcare BAN has been implemented using both front-end supported and self-supporting sensors. Figure 4 shows the self-supporting EISlab sensor [13] (left) and a TMSI front-end (right). Both approaches use Bluetooth for intra-BAN communication. The front-end also allows ZigBee as an alternative intra-BAN communication technology. Electrodes, a movement sensor, a pulse oximeter and an alarm button are examples of sensing devices that can be attached to the front-end.

The MBU was implemented on an iPAQ H3870. This device has built-in Bluetooth capabilities and can be extended with a GPRS jacket. Figure 5 shows a picture of the MBU that also runs a viewer application.

The BANip has been implemented using Java 2 Micro Edition (J2ME)[15]. The BANip is implemented on the MBU as an HTTP client that collects a number of samples into the payload of an HTTP POST request and invokes the post on the surrogate. We've used a standard HTTP proxy to act as a security gateway of the surrogate. In case the surrogate needs to control the MBU, these control commands are carried as payload of the HTTP reply.

The surrogate has been implemented using the Jini Surrogate architecture[16]. Jini provides the implementation for auto-discovery and registration of the BAN. In terms of the

Jini architecture the surrogate is a service provider. Other components, such as the BAN data storage component, are service users from the perspective of the surrogate.

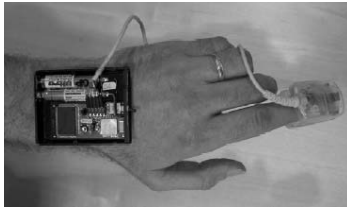


Figure 4 Self supporting sensor and a front-end



Figure 5 iPAQ H3870 acts as MBU

4 The MobiHealth Trials

The primary question addressed by the MobiHealth project was whether 2.5/3G communications technologies can support the MobiHealth vision, i.e., enable the move towards empowered managed care based on mobile health care systems. To obtain an (as much as possible) valid reply to this question, we organized and conducted nine different trials in four different countries around Europe, expecting that for some trials the existing infrastructure will be adequate while for others it may be insufficient. We must note however that the conducted trials were *not* clinical trials. The primary target of the project being the evaluation of the 2.5/3G infrastructures and *not* the validation of new medical tools and processes.

The trials also provide us the basis for a market validation of the system and service, towards further commercialisation. They are targeted at the areas of acute (trauma) care, chronic and high-risk patient monitoring and monitoring of patients in home-care settings. The trials cover a range of conditions including pregnancy, trauma, cardiology (ventricular arrhythmia), rheumatoid arthritis and respiratory insufficiency (chronic obstructive pulmonary disease), covering both use of patient BANs and health professional BANs (nurse BAN, paramedic BAN). The trials were selected to represent a range of bandwidth requirements: low (less than 12 Kbps), medium (12 – 24 Kbps) and high (greater than 24 Kbps) and to include both non-real time (like routine transmission of tri-weekly ECG) and real time requirements (e.g. alarms, transmission of vital signs in a critical trauma situation). For each application the generic MobiHealth BAN is specialized by addition of the appropriate sensor set and corresponding application software.

4.1 Trial 1 - Germany

Telemonitoring of patients with cardiac arrhythmia

The target group in this trial are patients with ventricular arrhythmia who are undergoing drug therapy. Cardiac arrhythmia is very common and in many cases is related to coronary heart disease. Around one million patients suffer from coronary heart disease in Germany today. In patients suffering from arrhythmia, ECG measurements have to be taken regularly to monitor

the efficacy of drug therapy. In order to save time and reduce costs, the patient is able to transmit ECG and blood pressure via GPRS from home or elsewhere to the health call centre, where the vital signs are monitored by a cardiologist. The intention is that irregular patterns in these vital signs will be detected quickly and appropriate intervention can be initiated. This trial is to evaluate how both patients and the cardiologist gain time and cost advantages, as well as to document processes for implementation.

4.2 Trial 2 - The Netherlands Integrated homecare for women with high-risk pregnancies

The trial will use the MobiHealth BAN to support integrated homecare for women with high-risk pregnancies. Women with high-risk pregnancies are often admitted to the hospital for longer periods of time because of possible pregnancy-related complications. Admission is necessary for the intensive monitoring of the patient and the unborn child. Homecare with continuous monitoring is desirable and can postpone hospitalisation and reduce costs, as well as offering more security for the mother and unborn child. In this trial, patients are monitored from home using the MobiHealth BAN and the (maternal and foetal) biosignals are transmitted to the hospital. An additional objective of the trial is to evaluate if such a solution postpones hospitalisation and reduces costs.

4.3 Trial 3 - The Netherlands Tele trauma team

MobiHealth BANs will be used in trauma care both for patients and for health professionals (ambulance paramedics). The trauma patient BAN will measure vital signs which will be transmitted from the scene to the members of the trauma team located at the hospital. The paramedics wear trauma team BANs which incorporate a video camera, an audio system and a wireless communication link to the hospital. The purpose of this trial is to evaluate whether use of mobile communications can improve quality of care and decrease lag-time between the accident and the intervention. When using telemetry technology, time can be saved and thus treatment and chances for patient recovery improved. Faster intervention is expected to increase survival rates and decrease morbidity. Parameters to be measured are breathing frequency, oxygen saturation, pulse rate, blood pressure, pupil size and reactions and amount of fluids infused. Video from the scene will be transmitted assuming UMTS availability.

4.4 Trial 4 - Spain Support of home-based healthcare services

This trial involves use of GPRS for supporting home-based care for elderly and chronically ill patients including remote assistance if needed. Patients suffer from co-morbidities including COPD. The MobiHealth nurse-BAN will be used to perform patient measurements during nurse home visits and the MobiHealth patient-BAN will be used for continuous monitoring during patient rehabilitation at home, or even outdoors. It is very important to facilitate patients' access to healthcare professionals without saturating the available resources, and this is one of main expected outcomes of the MobiHealth remote monitoring approach. Parameters

to be measured are oxygen saturation, ECG, spirometry, temperature, glucose and blood pressure.

4.5 *Trial 5 - Spain* *Outdoor patient rehabilitation*

The patients involved in this trial are chronic respiratory patients who are expected to benefit from rehabilitation programs to improve their functional status. The study aims to check the feasibility of remotely supervised outdoor training programs based on control of walking speed enabled by use of the MobiHealth BAN. The physiotherapist will receive online information on the patient's exercise performance and will provide feedback and advice. It is expected that by enabling patients to perform physical training in their own local settings, the benefits, in terms of cost and social acceptance, can be significant. Parameters to be measured are pulse oximetry, ECG and mobility with audio communication between patient and remote supervising physiotherapist.

4.6 *Trial 6 - Sweden* *Lighthouse alarm and locator trial*

The target group involved in the trials are patients at the Lighthouse care resource centre and also clients living at home, but with the common characteristic that all have an alarm system located in their room at the Lighthouse Centre or in their home. The current system does not allow the patient any freedom related to mobility and forces the patient to be trapped at home or in their room at the Centre. By replacing the fixed alarm system with the mobile MobiHealth system the patient can move freely anywhere. In addition, positioning and vital signs are monitored and video communication is planned with UMTS .

The effectiveness of the new GPRS/UMTS-based alarm and locating device (a variant of the MobiHealth BAN) will be tested according to several determining factors: safety, convenience, empowerment of user, mobility of user and improvement in efficiency of care given.

4.7 *Trial 7 - Sweden* *Physical activity and impediments to activity for women with RA*

Trial subjects will be women with Rheumatoid Arthritis. The use of the BAN together with the mobile communications will enable collection of a completely new kind of research data which will enhance the understanding of the difficulties and limitations which these patients face. The objective is to offer solutions that will make their lives easier.

By this collection of data, the scarce knowledge about what factors impede normal life will be supplemented and quality of life of RA patients may thereby be improved. By use of the MobiHealth BANs, the activity of the patients will be continually monitored. Parameters measured include heart rate, activity level, walking distance and stride length.

4.8 *Trial 8 - Sweden*

Monitoring of vital parameters in patients with respiratory insufficiency

The group of patients involved in the trial suffer from respiratory insufficiency due to chronic pulmonary diseases. These people need to be under constant medical supervision in case they suffer an aggravation of their condition. Besides needing regular check-ups, they are also dependent on oxygen therapy at home, which means oxygen delivery and close supervision. The use of the MobiHealth BANs is designed to enable the early detection of this group of diseases but also to support homecare for diagnosed patients by detecting situations where the patient requires intervention. The expected benefits are a reduction of the number of check-ups and hospitalisations needed, thus saving both time and money. Parameters measured are pulse rate, oxygen saturation and signals from a motion sensor (accelerometer).

4.9 *Trial 9 - Sweden*

Home care and remote consultation for recently released patients in a rural area

Home care services and the possibility of monitoring health conditions at a distance are changing the way of providing care in different situations. If suitable, home-based services are provided and patients do not need to be in hospital, for example they are recovering from an intervention. By investing in home care, hospitals have been able to significantly reduce pressure on beds and on staff time dedicated to the kind of patients named above. This trial tests transmission of clinical patient data by means of the MobiHealth BAN equipment to a physician or a registered district nurse (RDN) from patients living in a rural, low population density area. The expected benefit is that this solution will reduce the number of cases where the patient is supposed to visit a hospital for consultation unnecessarily.

5 Evaluation of the Trials

During the trials different types of data is collected in view of an evaluation of the results. The target of the evaluation is dual: first we want to verify the state of the UMTS (and GPRS) infrastructure and its suitability for mobile health applications, and second we want to explore the added value that the MobiHealth system can bring to different healthcare domains.

The evaluation of the trials will allow us to produce a set of suggestions to the wireless public network operators for the improvement, upgrade or possible modification of the infrastructure policies and mechanisms, so that applications like the ones developed in the MobiHealth project can be supported. This will be supported by concrete data indicating the (commercial) advantages that the operators will have in supporting m-health applications. Furthermore it will allow us to define a commercialisation strategy for the system and services developed, based on the capabilities of the network infrastructure, usefulness of the system and acceptance by the users.

We must note, once more, that by no means the evaluation of the trials will be done in view of a clinical evaluation of the system. A clinical evaluation is out of the scope of the project, the main target being the evaluation of the potential for m-health value added services over 2.5 and 3G communications.

At the moment of the writing of this chapter (January 2004), the trials are still ongoing and the evaluation was not yet completed. Nevertheless some preliminary results are available and will be presented in the following sections. We must however note that the results are

preliminary and that they have not yet been analysed. Thus definitive conclusions cannot be (yet) drawn.

5.1 Overview of the evaluation methodology

The trials are evaluated using a methodology developed in the project and different aspects of the trials are evaluated. Specifically we evaluate the trials from the technical point of view (technical evaluation), the medical point of view (end-user and social evaluation) and from the business point of view (market evaluation).

The technical evaluation focuses on the evaluation of the performance of the communication infrastructure used in the system. The main goal being the performance evaluation of the communication infrastructure, characterized in terms of: infrastructure availability, bandwidth characteristics, percentage of data loss / corruption, transmission delay and its variation (“jitter”).

The system performance related parameters are logged at the BAN side, while the generated traffic is logged by the 2.5/3G network measurement system. Logs at the BAN side declare if there were any problem regarding getting access to the network and the process of transmitting the data to the BEsys. The network log reports are used to verify if any of the logged problems at the BAN side could have been caused by the current status of the network during that time. Due to different restrictions it might not be always possible to log the network data during the trials. In this case general statistical data will be used instead.

In addition to the network performance the technical evaluation will also assess the overall system in terms of validity, accuracy and robustness of the Sensor / Actuator Service and application, the BAN and the intra-BAN communications, time delays etc.

The performance characteristics of the MobiHealth communication infrastructure are derived in two ways: objective and subjective evaluation.

The *objective evaluation* of the infrastructure includes active and passive measurements. For the active measurements an external data stream is generated (that is, we have no real MobiHealth data) and the performance characteristics of the communication paths are measured. The passive measurements will be performed in the up-and-running MobiHealth system so that real MobiHealth data are used. During the passive measurement phase, the participating operators will also perform some core-network data logging of the MobiHealth traffic characteristics.

The evaluation of the passive measurements is done in 4 steps. Step 1 involves testing on healthy volunteers in a rest state in a controlled environment (e.g., in a hospital setting) to compare the readings obtained from the BAN with readings taken from conventional equipment, and to give a first evaluation of usability, wearability, and patient satisfaction. Step 2 is like step 1 but the patients move around so that the effect of motion artefacts and wearability and functionality under more real-life circumstances can be assessed. In step 3 healthy volunteers or low risk patients are monitored in the home environment. Step 4 involves monitoring of patients in ‘uncontrolled’ real life situations over extended periods of time.

The *subjective evaluation* of the infrastructure’s performance will be done by the end-users (healthcare professionals) who will express their perceptions of functionality and performance characteristics as experienced during the usage of the MobiHealth system.

The end user evaluation describes the usability/acceptance of the MobiHealth Services over 2.5/3G infrastructure and it will seek the subjective opinion of users regarding the new services, their usability, user interaction, satisfaction, suitability, usefulness, acceptance, independence and experiences. Also the question about the perception on the performance characteristics of the system, like: system accuracy, validity, robustness, its speed or availability of the service will be addressed by the professional users. End users in this project are defined as the patients and the health care personnel who are involved in the trials and are using the MobiHealth system. In some trials relatives and next of kin will be involved, for instance in the trial that covers homecare and remote consultation for recently released patients in a rural area.

The results of the end-user evaluation are collected using diaries, questionnaires, interviews and some objective measurements, e.g. walking distance and step-length for mobility assessments. End-users evaluation results will be compared against the performance measurements of platform to analyse existence of expected correlations. For example, the receipt of a not useful poor quality ECG, which cannot be interpreted by a professional, that coincides with large delays and packet drops in the system indicates communication throughput problems.

The goal of **the market evaluation** is to provide a reliable and meaningful set of criteria which will allow to make valid statements and decisions regarding the market value and potential of the MobiHealth system in the respective trial settings which are envisaged within the project. The target will be the evaluation of market, health economic and commercial potentials that describe the different factors and requirements which determine the future market success of mobile healthcare systems in general and the MobiHealth system in particular. The factors which are important and decisive in this context include: health political issues, existing market structures and processes, market players, business scenarios, value chains, potential users, users' characterization (behaviour, acceptance requirements), health economic relevance, realization of market potentials (how much and when), barriers of entry, opportunities and threats.

Nevertheless given the short duration of the project and the trials, as well as the limited number of participants and the technical limitations, it will be hard to draw sound conclusions with regard to factors like health economic relevance or users' characterization. For these cases, extrapolation will be applied as far as possible to derive some possible scenarios on potential impacts.

The evaluation criteria include elements like readiness of the healthcare system to adopt mobile services, ability to integrate respective mobile services into existing market structures and processes, and ability to meet user requirements and gain acceptance for the respective mobile services.

5.2 *Some preliminary technical evaluation results*

Although at the time of writing of this paper the trials are still on-going and the measurements are yet to be completed, some preliminary results regarding the performance of the UMTS and GPRS networks and technical issues related to MobiHealth BAN can be sketched. We present here some of the results from the UMTS tests and trials performed in the Netherlands using the Vodafone pre-commercial UMTS network. We must note however that the MobiHealth project

is the *only* user of the Vodafone UMTS network in the Twente region. Thus we are running under the best-case environment, that is, on an empty network.

One of the first problems that we encountered in the use of the UMTS (and GPRS) networks is the *inverted producer-consumer* roles. Public networks were designed for applications where the end-user is a consumer of information, i.e, a typical user will send small requests and will receive massive data as a response. The MobiHealth system however is based on the reverse model: the end-user is the producer of information and not the consumer. The consequence of this reversal is that the network and terminal devices cannot support (in their present configuration) high bandwidth transmission emanating from the end-user. This is a limiting factor for the measurements that the MobiHealth system can send to the health broker.

To enhance portability and for being compatible with the operating systems available on portable telephones, the MobiHealth application on the MBU was programmed in Java under the CLDC Java Virtual Machine [17]. As a result we have been forced to use the HTTP protocol for transporting vital signals. However, the current HTTP protocol implementation under the CLDC Java VM does not allow for persistent HTTP connections. That means that whenever the MBU needs to send data it must establish a new TCP/IP connection. This is very expensive, in terms of performance. A better option would have been for the mobile telephones were able to use the CDC [18] platform that allows direct access to the TCP/IP layer.

A second issue related to the use of the HTTP protocol is the fact that every time a request is sent, the communication is blocked until an acknowledgment or reply is received. To solve this problem we used a technique called *chunking* [19] where multiple requests are sent without having to wait for a reply. However not all operators allow the use of chunking for their GPRS network. This eventually might cause standardization problems for services and applications that transmit continuous real time data over the GPRS and possibly UMTS

During the UMTS performance tests (active measurements) we performed tests trying to emulate a high load of the network by running 10 simultaneous UMTS transmissions. The tests (which are still on-going) indicate a performance degradation (network failure) when high bandwidth from 10 UMTS connections are simultaneously transmitted (from the same room, with each UMTS connection running from its own unique terminal). The reason for this failure is not clear yet we hope to have more data and information at the end of the tests.

On the positive side we were able to confirm the stability of the Vodafone UMTS network in the Netherlands. Tests done with a moving station (a car roaming within the Enschede coverage area) allowed us to maintain a connection of at least 64Kbps (up and down link) crossing over cell boundaries and under different speeds. The maximum bandwidth available for a fixed station of 64Kbps uplink and 384 downlink is readily available and stable throughout the coverage area (our terminal devices – Nokia UMTS telephones – do not allow us to obtain higher bandwidths).

The available data bandwidth over GPRS (and UMTS) depends on the strength of the signal at the user location. Although the GPRS and UMTS telephones do indicate the signal strength during operation, this is not the case for the PCMCIA cards integrated with the iPAQ. Some PCMCIA cards allow the control of the signal strength using proprietary software, *but only during set up*. During data transmission the signal strength information is not available. However this information is of major importance for the MobiHealth application, since it will allow us to estimate the available bandwidth and to control the data transmission rate accordingly. Currently, we have the situation that when transmitting at high bandwidth at an area with strong signal and we pass to an area where the signal is low, we are not able to lower the data transmission rate and as a result the system gets overloaded. We thus believe that the signal rate as well as the encoding schema used during the transmission should be available to

the application under a standardized API for all types of GPRS/UMTS terminals, whether these terminals are PCMCIA cards or regular mobile phones.

6 Conclusions

At time of writing the MobiHealth project has been running for 20 months (since May 2002). In the rather short duration of the project a great many problems and challenges have been encountered and much progress has been made. The starting point was a vision of ubiquitous mobile health services based on Body Area Networks. During the project we have designed and prototyped a health BAN and a BAN service platform and developed services for different patient groups according to the requirements specified by the clinical partners. Patient trials have begun and evaluation data are under collection for further analysis.

MobiHealth aims to give patients a more active role in the healthcare process while at the same time healthcare payers are able to manage costs more directly. The healthcare BAN and supporting service platform is an emerging technology that promises to support this aim.

In a collaborative effort between healthcare professionals and technology experts nine trials have been defined. We expect to use these trials to evaluate the functionality and performance of the BAN and service platform. The main element of this evaluation will be an analysis of the suitability of 2.5/3G public wireless infrastructures for the support of remote healthcare monitoring. We intend to evaluate the social impact, user satisfaction and usability of the BAN on the patient and professional experience. Trials have already started and initial feedback indicates that our remote healthcare monitoring system is an important technology that facilitates the move towards empowered managed care.

MobiHealth has resulted in an early prototype of the BAN, engineered mainly by integration of existing technologies without focusing on miniaturization or optimisation of power consumption. The main focus has been on the architecture, design and implementation of an m-health service platform. The result is a first version of a service platform whose architecture is comprised of a set of clearly defined components.

It should not be thought however that all problems have been overcome even with use of current technologies. Ambulatory monitoring is more successful for some biosignals than others, for example some measurements are severely disrupted by movement artefacts. Some monitoring equipment is still too cumbersome for ambulatory use, because of the nature of the equipment or because of power requirements. In the area of wireless (tele)communication technologies (even with 2.5 and 3G) we still suffer from limited bandwidth for some applications, such as those which require serving many simultaneous users with applications requiring high bandwidth.

The use of BANs and wireless communications in personal healthcare systems still raises important challenges relating to security, integrity and privacy of data during transmission. This applies to both local transmission (eg. intra-BAN) and long range (eg. extra-BAN) communications. End-to-end security and Quality of Service guarantees need to be implemented. Safety of hardware (eg. electrical safety, emissions, interference) and reliability and correctness of applications must also be a priority in deployment of mobile services. Comfort and convenience of sensors or BANs worn long term for continuous monitoring is important for usability and user acceptance. Timeliness of information availability in the face of unreliable performance of underlying network services is another issue. Provision of seamless services across regional and national boundaries multiplies these difficulties. Powering *always on* devices and continuous transmission will continue to raise technical

challenges. Business models for healthcare and accounting and billing models for network services need to evolve if technical innovations are to be exploited fully. Standardisation at all levels is essential for open solutions to prevail. At the same time specialization, customisation and personalisation are widely considered to be success criteria for innovative services.

Although our formal work in the MobiHealth project will be completed in the end of February of 2004, plans are underway for the creation of a venture for the further development and commercialisation of the results. The great interest shown by healthcare organizations and commercial companies, as well as the products that become available in the market every day and the interest shown by patients encourages us to proceed as fast as possible in the creation of a company that will promote and commercialise the MobiHealth services and platform. We expect that by the end of the 2004 to have a first version of a commercial system available to interested users in different European countries.

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