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Mobile Patient Monitoring: The MobiHealth System

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ABSTRACT

The forthcoming wide availability of high bandwidth public wireless networks will give rise to new mobile healthcare services. To this end, the MobiHealth project has developed and trialed a highly customisable vital signs monitoring system based on a body area network (BAN) and a mobile-health (m-health) service platform utilising next generation public wireless networks. The developed system allows the incorporation of diverse medical sensors via wireless connections, and the live transmission of the measured vital signs over public wireless networks to healthcare providers. Nine trials with different healthcare scenarios and patient groups in four different European countries have been conducted. These have been performed to test the service and the network infrastructure including its suitability for mobile healthcare applications. Preliminarly results have documented the feasibility of using the system, but also demonstrated logistical problems with use of the BANs and the infrastructure for transmitting mobile healthcare data.

INTRODUCTION

The expansion and availability of high (mobile) bandwidth (General Packet Radio Service [GPRS] and Universal Mobile Telecommunications System [UMTS]) combined with the ever-advancing miniaturisation 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 healthcare. In the future, patients will be able to receive medical advice from a distance and be able to send full, detailed and accurate vital signs measurements irrespective of where they are. This data will be of an equivalent standard to that obtained in a medical centre, implementing the concept of 'ubiquitous medical care'.

In keeping with this vision, the MobiHealth project (supported by the Commission of the European Union in the frame of the 5th research Framework

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under project number IST-2001-36006) has developed an innovative value-added mobile health service platform for patients and health professionals. The service enables remote patient monitoring through the use of advanced wireless communications and integration of sensors to a wireless body area network (BAN). It permits remote management of chronic conditions and detection of health emergencies whilst maximising patient mobility.

THE MOBIHEALTH SYSTEM

The MobiHealth system provides a complete end-to-end m-health platform for ambulant patient monitoring, deployed over UMTS and GPRS networks. The MobiHealth patient/user is equipped with different sensors that constantly monitor vital signals, e.g. blood pressure, heart rate and electrocardiogram (ECG). These are interconnected via a healthcare *body area network* (BAN)[1–4]. In essence this consists of sensors, actuators, communication and processing facilities connected via a wireless network. This is worn on the body and moves around with the person, i.e. the BAN is a roaming unit.

The central point of the healthcare BAN is the *Mobile Base Unit* (MBU). This aggregates the vital sensor measurements and transmits them via UMTS or GPRS to the back-end system. The back-end system can be located within the healthcare provider premises or be part of the wireless services provider. From there the measurements are dispatched to the healthcare provider where they are monitored by medical personnel. At present automated monitoring and patient feedback is not supported by the MobiHealth system.

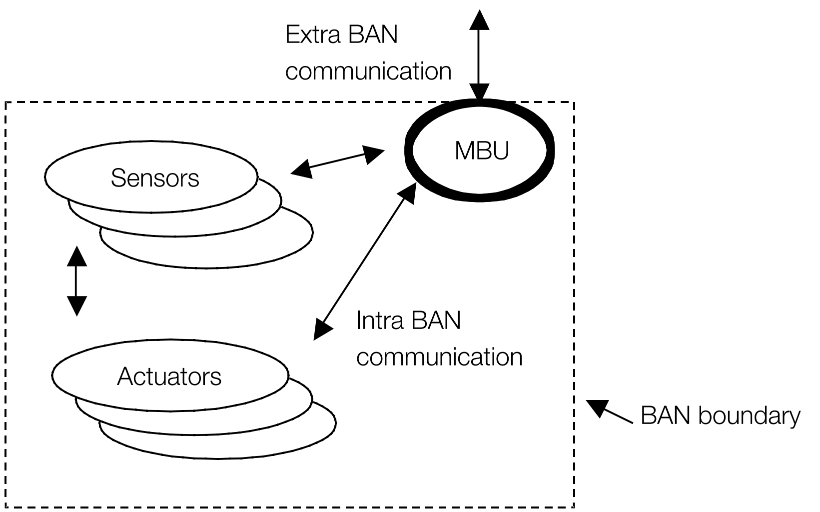

Figure 1. *Healthcare BAN architecture*

Communication between entities within a BAN are referred to as *intra-BAN communication*. *Extra-BAN communication* is performed through the Mobile Base Unit and enables remote monitoring. Intra-BAN communication is based on short range wireless networks like Bluetooth[5] and Zigbee[6], while extra-BAN communication employs GPRS and UMTS. Figure 1 shows the architecture of a healthcare BAN.

The sensors used in the BAN are responsible for the data acquisition process. They monitor and capture a physical phenomenon, such as patient movement, muscle activity or blood flow. This is 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 their own 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 to its own internal clock and may have a different sample frequency. Consequently, mechanisms for synchronisation 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 synchronisation between sensors.

Service Platform Architecture

Collecting and transmitting 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 healthcare agent 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 executed. The rounded boxes represent the functional layers of the architecture. The m-health service

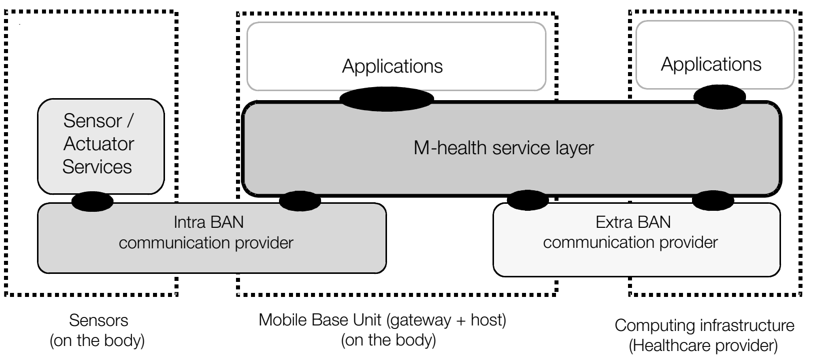

Figure 2. *Service platform functional architecture*

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.

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, e.g. a call centre or secondary care centre. 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.

Figure 3. *Self supporting sensor (left) and complete front-end system with ECG and oxygen saturation sensors*

Figure 4. *iPAQ H3870 acts as MBU*

The healthcare BAN has been implemented using both front-end supported and self-supporting sensors. Figure 3 shows the self-supporting EISlab sensor[7] (left) and a TMSI front-end (right) with ECG and oxygen saturation sensors. Both approaches use Bluetooth for intra-BAN communication. The front-end also allows ZigBee as an alternative intra-BAN communication technology. ECG 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 extension jacket. Figure 4 shows a picture of the MBU that also runs a viewer application.

THE MOBIHEALTH TRIALS

The primary question addressed by the MobiHealth project was whether 2.5G and 3G generation communications technologies can support the MobiHealth vision, i.e., enable empowered managed care based on mobile health care systems. To address this question, we organised and conducted nine trials in four European countries. These trials allowed us to identify problems and issues in the development of mobile health services and identify limitations and shortcomings of the existing and forthcoming public network infrastructure. It should be made clear that the primary aim of the project was to evaluate 2.5/3G infrastructures and *not* to clinically validate new medical tools and processes.

The trials were targeted at the areas of acute (trauma) care, chronic and high-risk patient monitoring, and domiciliary care. A range of medical conditions was covered including pregnancy, trauma, cardiology (arrhythmias), rheumatoid arthritis (RA) and respiratory insufficiency (chronic obstructive pulmonary disease). In cases of trauma and other acute situations, the BANs were applied to the patients by medical staff, e.g. nurses or paramedics. In other situations the patients usually applied the BAN themselves.

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 (e.g. routine transmission of tri-weekly ECG) and real-time requirements (e.g. alarms or transmission of vital signs in a critical trauma situation). For each application, the generic MobiHealth BAN is customised by addition of the appropriate sensor set and corresponding application software.

The participating countries and trials were:

1. Germany – Telemonitoring of cardiac arrhythmias.
2. The Netherlands – Integrated homecare for high-risk pregnancies.
3. The Netherlands – Teletrauma.
4. Spain – Support of home-based healthcare services.
5. Spain – Outdoor patient rehabilitation.
6. Sweden – Lighthouse alarm and locator trial.

7. Sweden – Physical activity and impediments to activity for women with RA.
8. Sweden – Monitoring of vital parameters in patients with respiratory insufficiency.
9. Sweden – Home care and remote consultation for recently hospitalised patients in a rural area.

More details on the trials can be found on the project site http://www.mobihealth.org.

Data collected in the trials was aimed at:

- Verifying the state of the UMTS (and GPRS) infrastructure and its suitability for mobile health applications.
- Exploring the added value that the MobiHealth system can bring to different healthcare domains.

RESULTS

Analysis of the project was performed early in 2004 whilst the trial was still in progress. The data presented here pertains to the Twente region in the Netherlands where the UMTS network is provided by Vodafone. It should be noted that the MobiHealth project was 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.

The stability of the Vodafone UMTS was demonstrated by tests done with a moving car travelling in the Enschede area. We were able to maintain a connection with a nominal capacity of 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 384Kbps downlink was readily available and stable thoughtout the coverage area (our terminal devices – pre-commercial Nokia 6650 UMTS telephones – do not allow us to obtain higher bandwidths).

A fundamental problem was encountered relating to the use of the UTMS (and GPRS) networks. The public networks were designed for applications where the end-user is a consumer of information, i.e. a typical user will send small amounts of data and receive large amounts of data. The MobiHealth system, however, is based on the reverse model: the end-user is the producer of information and not the consumer. The present network and terminal devices in their present configuration are not designed to support high bandwidth transmission emanating from the end-user. This limits the measurements that the MobiHealth system can send to the healthcare provider.

Problems were also encountered with the HTTP (HyperText Transfer Protocol) for transporting vital signals. To enhance portability and compatability with the operating systems available on portable telephones, the MobiHealth application on the MBU was programmed in Java under the Connected Limited Device Configuration (CLDC) Java Virtual Machine (VM)[8]. 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 (Transmission Control Protocol/Internet Protocol) connection. This, however, impedes performance. A possible solution would be for the mobile telephones to be able to use the Connected Device Configuration[9] 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 overcome this problem we used a technique called *chunking*[10]. This enables multiple requests to be 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 standardisation 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 on the network by running ten simultaneous UMTS transmissions. The tests indicated a performance degradation when high bandwidth from ten 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, however, not clear at present and is being further investigated.

DISCUSSION

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

MobiHealth has resulted in an early prototype of a BAN, engineered mainly by integration of existing technologies without focusing on miniaturisation 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.

Preliminary trials have shown the feasibility of using the system, but a number of problems have been encountered. Not all of these problems can be overcome with the 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 GPRS and UMTS) we still suffer from limited bandwidth for some applications, such as those which require monitoring many simultaneous signals per user.

The available data bandwidth over GPRS (and UMTS) depends also 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 (Personal Computer Memory Card International Association) cards integrated with the iPAQ. 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 a situation where, if we are transmitting at high bandwidth in an area with a strong signal and pass to an area where the signal is weak, we are unable to lower the data transmission rate and consequently lose the connection. 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 standardised application program interface for all types of GPRS/UMTS terminals, whether these terminals are PCMCIA cards or regular mobile phones.

The use of BANs and wireless communications in personal healthcare systems will also raise important challenges relating to security, integrity and privacy of data during transmission. End-to-end security and quality of service guarantees need to be implemented. Safety of hardware (e.g. 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 specialisation, customisation and personalisation are widely considered to be success criteria for innovative services.

Despite all these problems, there is much interest and enthusiasm for the project both from patients and healthcare professionals. We will continue to develop and implement the system and expect that it will be available commercially in several European countries during 2005.

CONCLUSION

The results of the project include an architecture for, and a prototype of, a generic service platform for provision of ubiquitous healthcare services based on body area networks. The MobiHealth System can support not only sensors, but potentially any body-worn device. Consequently the system has potentially many applications in healthcare and will enable a variety of healthcare services to delivered in the community. However, a number of technical problems remain to be resolved before the system can be used in routine practice.

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