

Body sensor networks for Mobile Health Monitoring: experience in Europe and Australia

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Abstract—Remote ambulatory monitoring is widely seen as playing a key part in addressing the impending crisis in health care provision. We describe two mobile health solutions, one developed in the Netherlands and one in Australia. In both cases a patient's biosignals are measured by means of body worn sensors which communicate wirelessly with a handheld device. Alarms and biosignals can be transmitted over wireless communication links to a remote location, and a remote health professional can view the biosignal data via a web application. The clinical purposes are similar, however the technological approaches differ in some respects. We compare the two approaches and the experience gained working with a number of different patient groups and clinical specialties during trials in Europe and Australia.

Keywords- telemonitoring, teletreatment, mobile technology, mobile healthcare solutions, Personal health monitoring.

1. Introduction

M-health systems are attracting increasing interest since they offer personalised healthcare services to the patient whilst promising to alleviate pressure on the overburdened healthcare system by improving daily disease management, enabling automatic emergency and trend detection and facilitating self-care. Many m-health systems are already in routine clinical use, typically incorporating a wearable or implanted device and running embedded software to perform a specific set of functions around one clinical application. We distinguish *monitoring* services from services which also provide some kind of *treatment* or intervention. Pacemakers, for example, combine monitoring with intervention. Such a system runs *autonomously* and *transparently* (the patient need not be aware of it or interact with it) in contrast with personal health systems where the patient actively interacts with the system; hence we distinguish also *personal* mobile services used by the patient to aid daily self-care. *Local*, personal services, which may be delivered by a standalone mobile system, are distinguished from *teleservices*, which involve long range communication with a remote healthcare location or health professional.

Many systems available today are closed proprietary systems which provide a specific set of condition-specific services, eg. monitoring and disease management functions. In this paper we present a more generic, open approach which we believe will lead to more flexible and adaptable personal and

telehealth services in future. We examine two different generic approaches developed by two groups of researchers: one in Australia and one in Europe.

Members of the Telemedicine Group at the University of Twente in the Netherlands have been investigating the application of Body Area Network (BAN) technology in a number of clinical settings in order to offer *remote monitoring and treatment* services. The European system is known as MobiHealth. Several variants of the system were developed during a number of projects starting with IST MobiHealth [1-2] and currently continuing in MYOTEL [3]. Figure 1 shows the MYOTEL BAN.

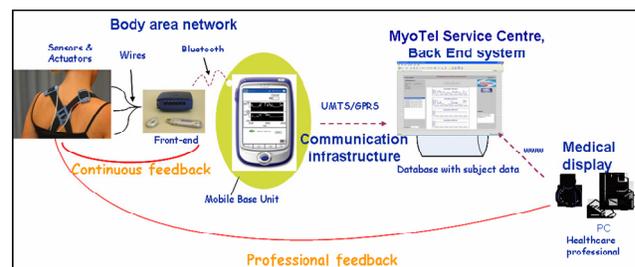


Figure 1. Myotel teletreatment BAN

An alternative approach is applied at the University of Technology, Sydney, where a Personal Health Monitor (PHM), originally focusing on *local, personal* m-health services, has been developed and applied in various clinical settings [4-6].

With both systems the patient wears body worn sensors and uses a handheld device which receives output from the sensor systems, runs a local application and acts as a communications gateway for (possible) onward transmission of data to a remote healthcare location. In the Australian system (Figure 2) the handheld device is a Microsoft Windows mobile phone. The European system has been implemented on a number of different PDAs and mobile phone platforms.



Figure 2. Personal Health Monitor

The two approaches share similar clinical goals, namely provision of routine chronic disease management functionality and/or detection of medical emergencies in different clinical settings. In both cases the philosophy is to design a generic mobile solution which can be adapted to different clinical applications, which is easy to wear and use and is as unobtrusive as possible.

However the two teams utilise different approaches and different development technologies. Here we present the two approaches and compare the experience gained working with different patient groups and different clinical specialties in Europe and Australia.

In Section 2 a generic architecture for m-health systems is presented. In Section 3 this architecture is used to compare the two systems. Section 4 describes the clinical applications developed so far by the two teams. Section 5 compares experience with users and Section 6 presents discussion and conclusions.

2. A Generic Architecture for M-Health

Here we describe a high level architecture (Figure 3) and terminology originally developed as part of the European research and apply it to compare the two systems and to test the genericity of the architecture.

We view a *BAN-based m-health system* as a set of deployed BANs and a Back End. Communication between BANs and the Back End is via so-called extraBAN communication. To support pervasive services and full mobility for the user extraBAN communication should be wireless. IntraBAN communication may be wired, wireless or a mixture of the two.

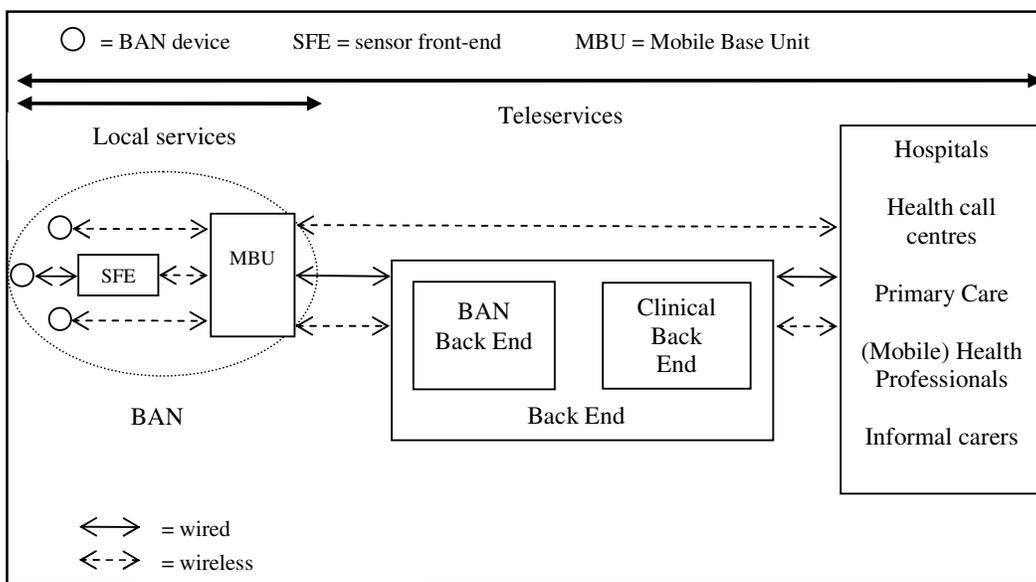


Figure 3. Generic architecture for m-health

A health BAN is defined as a network of communicating devices worn on, around or in the body which provides mobile health services to the user. A BAN consists of a Mobile Base Unit (MBU) and a set of BAN devices (e.g. sensors, actuators or other 'wearable devices'). The MBU acts as a processing platform and communications gateway and is currently realised as a software application running on a handheld device. BAN data may be processed locally within the BAN and/or remotely, the latter implying transmission of data to a remote location. Front-end supported sensors are powered by a sensor front end

which also digitizes and filters the raw analogue signal before transmitting the data over a wireless link to the MBU.

In general, a health BAN may act as a standalone device providing personal local services to the patient. At the other end of the spectrum, all BAN data may be transmitted onward for processing, or a combination of local and remote processing may be used. If a remote user (human or software) is involved and extraBAN communication occurs then we can regard the m-health service as a telemedicine service.

In the Back End we distinguish functions which are concerned with management of BANs, their devices and BAN data from the clinical back end functions, which support application specific functionality and which may interface to healthcare providers' information systems.

3. Comparison of the implemented systems

In this section we compare the two systems according to the architectural concepts outlined in the previous section. Table 1 lists the respective features of the two systems by the major components identified in the architecture.

TABLE I. Features of the two systems by architectural components

Component	Personal Health Monitor	MobiHealth
BAN devices	<ul style="list-style-type: none"> Off-the-shelf sensor systems (front end supported). Sensors are non-invasive, good quality/price ratio, Bluetooth enabled. Sensors: 1 channel ECG, weight scale, accelerometer, blood pressure monitor, blood glucose meter, pulse oximeter Other: GPS. 	<ul style="list-style-type: none"> Sensors, actuators, any other wearable device with (wireless or wired) communications interface. Sensors: 3, 4 and 9 channel ECG, surface EMG, pulse oximeter, respiration sensor, temperature sensor, activity sensors (step-counter, 3D accelerometer). Actuators: tactile feedback. Other: GPS, alarm button.
Sensor Front End	<ul style="list-style-type: none"> Subcomponent of commercial sensor system incorporating embedded software for signal processing. 	<ul style="list-style-type: none"> Commercial sensor Front Ends (re)developed by industrial partners, with some programming of DSP to perform additional biosignal and other processing.
MBU	<ul style="list-style-type: none"> Implemented on a mobile phone. Any smart phone running Microsoft Windows Mobile OS. 	<ul style="list-style-type: none"> Implemented on various mobile phones and PDAs. Any mobile platform capable of running Java VM and RMI.
Software on the MBU	<ul style="list-style-type: none"> Generic interface showing live data, reminders, battery status. Admin. interface to configure reminders, sensors. Algorithms to analyse ECG data and to advise user. 	<ul style="list-style-type: none"> Application specific functionality and GUI running over generic BAN software layer and protocol stack. Example: seizure detection algorithm for epilepsy.
Processing on the MBU	<ul style="list-style-type: none"> Philosophy: process locally all that can be automated and within processing capabilities of the mobile phone. This limits transfer of unnecessary data and provides immediate feedback to the patient. Positioning (also indoors) using WiFi, GSM cell id and GPS. Personalisation of sensor thresholds and emergency settings. Customized audio warnings and informative messages. Reminders per sensor. 	<ul style="list-style-type: none"> Philosophy: design and optimize total chain of processing for each specific application; attempt to manage QoS in wireless and mobile environment by performing dynamic (re)allocation of processing tasks across the m-health service platform including the MBU. Positioning (outdoors) using GSM cell-id and GPS. Context aware applications (adaptation to context including communications environment and patient's environment).
IntraBAN Communications	<ul style="list-style-type: none"> Wired, wireless (Bluetooth). 	<ul style="list-style-type: none"> Wired, wireless (Bluetooth).
ExtraBAN Communications	<ul style="list-style-type: none"> 3G, GSM, SMS, Internet. Phone and SMS numbers can be personalised . 	<ul style="list-style-type: none"> GPRS, UMTS, WiFi, Internet, SMS. Vertical handover between transmission technologies (in response to changing cost, bandwidth availability, network congestion etc.).
Back End	<ul style="list-style-type: none"> Any ISP offering Microsoft ASP.NET web hosting. Generic interface for live data showing patients needing attention. Generic interface for PHM administration. Specific Interface for the specialist (cardiologist, personal assistant). 	<ul style="list-style-type: none"> BAN Back End runs on PC or laptop set up as Jini server. Jini Surrogate Architecture used to represent and manage BANs, BAN devices and BAN data and give physicians access to BAN data and BAN management functions. Physician access via a generic m-health portal (web application) which is customized for each clinical application.
Processing on Back End	<ul style="list-style-type: none"> Triage of life data which can be personalised to the application domain. 	<ul style="list-style-type: none"> Generic BAN functionality. Application functionality specific to each individual clinical application and patient and HP user requirements.

	<ul style="list-style-type: none"> • Viewing and reporting for physician. • Physician can update sensor thresholds. • Remote management of PHM equipment and patients. • Password protected viewing by the patient (limited view). • Synchronisation between MBU and Back End. 	<p>Generally, viewing, streaming and management services for BANs and BAN data, analysis and interpretation algorithms, alarms, geospatial and location-based services.</p> <ul style="list-style-type: none"> • HPs can switch on BANs and BAN devices, alter sampling frequencies etc. • Mechanisms for feedback and treatment from HPs. • Various security and access control mechanisms.
Trial Patient group(s)	<ul style="list-style-type: none"> • 1 trial group: 70+ cardiac patients. • Trial in one centre in Sydney. • English speaking, Multi- ethnicity, 22-90 years. • Low-medium risk patients. 	<ul style="list-style-type: none"> • 17 trial groups over 4 projects. • Multi centre international trials in Europe. • Multi-language. • Low risk patients.
Clinical specialties/settings	<ul style="list-style-type: none"> • Cardiology. • General well being. • Chronic disease management. • Rehabilitation. 	<ul style="list-style-type: none"> • Cardiology. • Obstetrics. • Trauma care. • Rheumatology. • Psychiatry. • Pulmonary medicine. • Gerontology. • Neurology.
Clinical applications	<p><i>Monitoring</i></p> <ul style="list-style-type: none"> • Cardiac Rhythm Monitoring. • Cardiac rehabilitation. • Primary prevention. 	<p><i>Telemonitoring:</i></p> <ul style="list-style-type: none"> • Ventricular arrhythmia. • High risk pregnancies. • Acute trauma • Rheumatoid arthritis. • Recently discharged patients in remote locations. • Mental health problems. • COPD rehabilitation. • Elderly patients with co-morbidities including COPD. • Epilepsy • Uncontrolled movements in spasticity. <p><i>Telemonitoring/treatment:</i></p> <ul style="list-style-type: none"> • chronic pain with whiplash or • with work-related neck and shoulder pain

4. Clinical applications

A. *Personal Health Monitor*

Applications currently available include Cardiac Rhythm Monitoring (CRM), Cardiac Rehabilitation and primary prevention. The CRM application aims at detecting cardiac arrhythmia events which are not always detected by a Holter or Event monitor due to their sporadic nature. The study also investigates the usability and practicability of the system from both patients' and physicians' perspectives. A secondary aim is to investigate whether use of the PHM provides clinically meaningful reassurance to patients with suspected arrhythmias and other cardiac conditions.

The Cardiac rehabilitation application aims at remote monitoring of a patient's progress by a physician as well as motivating the patient to do his/her exercises. Studies show that, in order to improve long term clinical outcomes, patients need to make lifestyle changes following myocardial infarction

or coronary bypass surgery. Many fail to do so. We investigate whether the PHM system can aid and motivate patients to achieve these life style changes by giving reminders and monitoring progress.

B. *MobiHealth BAN*

The mobile services provided can be characterized as telemonitoring or teletreatment services. Multi-centre international trials have been conducted in The Netherlands, Germany, Spain, Sweden and Cyprus. Different variants of the BAN have been trialled on a number of patient groups during the course of several research projects starting in 2002 with the MobiHealth project. Patients with ventricular arrhythmias were monitored by a health call centre. They wore BANs designed to detect dangerous arrhythmias as well as longer term trends in cardiac function. Pregnant women were monitored in order to detect premature labour and foetal distress. In the trauma trials ambulance paramedics used paramedic BANs to transfer image information from the scene to the hospital and applied trauma patient BANs to casualties to transmit vital signs to the hospital. Physical activity monitoring of women with

rheumatoid arthritis was conducted in order to gather research data. Patients recently discharged from hospital to remote rural locations were remotely monitored by a physician or a registered district nurse, with the objective of preventing unnecessary (re)hospitalizations. Patients with mental health and other problems supported by a home alarm system were given a BAN equipped with positioning and an alarm button. The objective was to support these patients outside the home, thus freeing them up to full mobility. COPD patients used BANs for monitoring at home and during outdoor exercise during rehabilitation. Another trial used telemonitoring in homecare for elderly chronically ill patients.

Cardiac, pregnancy and COPD monitoring were further trialled during the HealthService24 project.

In Awareness epilepsy patients, chronic pain patients and patients with uncontrolled movements in spasticity were monitored.

With Myotel we introduce *teletreatment*. Teletreatment involves local biofeedback and advice from a remote clinician. Telemonitoring and treatment services are trialled on chronic pain patients including patients with whiplash and patients with work-related neck/ shoulder pain.

5. Experience with users

A. Australian trials

To date 70 low-medium risk cardiac patients, aged 22 to 90 years old used the PHM system at a Sydney Hospital (Cardiology Department). The patients were given a heart monitor and a mobile phone to monitor and record their cardiac rhythm for a few weeks in their normal environment

The trial already demonstrated that the detection of important cardiac arrhythmias is feasible using the PHM system compared to conventional Holter monitors. The ECG signal quality is in the majority of cases of sufficient quality for a cardiologist to make an assessment.

Patients are able to record their cardiac rhythm when they feel something and the PHM records automatically if it detects an abnormal rhythm. "Catching" an arrhythmia event greatly improves satisfaction for those patients for whom nothing showed up on an ECG taken by the cardiologist. Most patients had no difficulty using a mobile phone and ECG sensor and the PHM application is straightforward to use. All patients who had used a Holter monitor found the PHM far less intrusive and more practical. Patients leading an active life appreciated the fact no one could see they were wearing sensors and being monitored .

B. European trials

Our experience working with healthcare organizations and clinicians has been almost exclusively positive over the course of the BAN research. However the clinicians who initiate or join such projects are often the enthusiastic early adopters of technology, so are not necessarily representative of all their professional colleagues. Technical failures (such as system instability and loss of network connectivity), sub-optimal interface design and a difficult (re)start sequence

understandably cause irritation and confusion to users. Notwithstanding some such technical problems in the first generation prototypes the utility of the telemonitoring service was acknowledged by all classes of user: professionals and patients, who agreed that 'a stable commercial product would be very useful' and "the overall evaluation of the MobiHealth system showed that *the need for, and advantages of, the system were clear to all users*". Preliminary results from Myotel indicate that continuous *local* biofeedback enables chronic pain patients to adapt their behaviour 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. Patients reacted positively to a feature allowing them to view their biosignals in real time on the MBU and quickly learnt to 'read' the displays and use them to improve relaxation [3].

6. Discussion and conclusions

The PHM system adopts the policy of local processing, with interpretation algorithms running locally on the mobile system worn by the patient. In contrast the MobiHealth BAN is designed to be inherently a telemedicine system so a core feature is transmission of data to a remote system or user. An added advantage of the distributed system is that more computationally expensive processing, which may exceed the capacity of the mobile device, can be applied at the server side. However delays and other complications may also arise through dependence on long range wireless links.

The Australian team made a decision to focus on non-invasive applications. For the European team, all applications so far have been non-invasive, but minimally invasive systems, including the use of implants, are not ruled out. The Australian PHM system originally aimed to provide personal mobile health services primarily for use by patients; later the back end web services for clinical users were added. In contrast, for the European team the *teleservice* aspect was central from the outset. The Australian PHM system targets *personal monitoring* specifically and associated disease and personal health management services, whilst the MobiHealth vision was always to provide m-health services for patients and health professionals by enabling virtual health care teams. From the start the MobiHealth team aimed at *teletreatment* as well as telemonitoring. The European team also included the notion of BANS for health professionals as well as patients from the outset [2].

The European team began by defining a generic architecture for the MobiHealth BAN and its supporting system. The generic BAN is then specialised for each clinical application by integrating a specific set of devices and implementing the appropriate application functionality. In the current exercise, by applying the generic architecture we found that the concepts could be mapped onto the Australian PHM system and correspondences and differences could be identified by reference to that architecture.

We express the generics using a layered architecture view, with the application specifics at the top layer. Where MobiHealth started with generics and moved to specialization, the PHM approach was to start with one clinical application

and separate generic functionality from application details, then to transfer the generics from the first clinical application to other applications within cardiology. In contrast the MobiHealth BAN was applied in parallel to clinical settings from different specialties since the first prototype systems. The PHM system will be applied to other specialties than cardiology and already has other sensors integrated which can be reused in other applications (Weight scale, Blood Pressure monitor, Blood Glucose monitor and Pulse Oximeter).

The emphasis on adaptability and genericity, and the level of ambition, together with the essential telemedicine dimension, come at the cost of a certain level of complexity, making the MobiHealth system relatively heavyweight compared to the PHM system, with its leaner, more light weight approach.

Determinants for the success of telemedicine have been identified as (1) Technology, (2) Acceptance, (3) Financing, (4) Organization and (5) Policy and Legislation [7]. Since both the PHM and the MobiHealth BAN are targeting the same global market, we face the same challenges in terms of financing, policy and legislation. We therefore focus here on Technology and Acceptance.

A. *Technology*

The PHM uses off-the-shelf sensors. They are available on the market and their technology is mature. This means that to use the PHM for independent personal monitoring, a user only needs to have a Microsoft Windows Mobile phone, and to buy or rent the sensors. The user can then download the software onto the mobile phone and use it just like any other Windows Mobile application. Another advantage of using off the shelf sensors is that the health professionals trust those devices if they are FDA, TGA and/or CE, approved. Patients can claim sensor rental or purchase from Medicare or their private health insurance in some countries (e.g. in Australia, blood pressure and blood glucose monitors are reimbursed by health insurers).

The PHM users had no real problem with the battery life of the mobile phone. Most people nowadays are used to recharging their phone regularly. The limited battery life of the mobile devices has been more problematic for the MobiHealth BAN due to the more experimental nature of the sensor front ends used.

For the younger generation, using a mobile phone for local processing of sensor data is a natural choice. It might be expected that simpler devices would be more suitable for patients in their 70s or older. However, during the PHM trials, elderly patients were able to use the personal health monitoring application even if they never used a mobile phone before. Simplicity and motivation, not age, seem to be the key factors for technology acceptance.

The European team always took the view that to support pervasive services and full mobility for the user extraBAN communication should be wireless. However, the PHM, with good reason, uses both wireless and wired communication extraBAN. The PHM has an option to use wired (USB) communication between phone and PC to allow synchronisation of non-urgent data with the web service over

ADSL. It might seem awkward to European, Canadian and US readers who are used to excellent wireless coverage but this is a necessity in countries like Australia where wireless coverage is patchy and/or costly.

Both PHM and MobiHealth BAN provide secure web access to display data and present information using different views. The PHM team chose also to give patients access to some data. This allows them for example to check on their progress or to show their data to their GP. In the MobiHealth system, the emphasis has been on clinician access to data but patient access to data can be given depending on the application requirements. An example is the Myotel myofeedback BAN [3], which allows patients to view their biosignals real time on the MBU.

MobiHealth BANs do not operate in isolation but are supported by an m-health service platform. We make a clear separation between the BAN Back End System and the clinical back end. The professional users at the clinical back end manage BANs and access BAN data via the m-health portal. A corollary is that the MobiHealth BAN cannot operate in standalone mode. In contrast the Australian system can operate standalone as a personal mobile service and can provide useful services in the absence of cell phone coverage. The PHM system works even if none of the designated sensors are connected.

The development environment used for the PHM is C# and .NET compact framework, so the PHM system is tied into Microsoft's Windows Mobile operating system. However the system can be deployed onto any mobile phone running Windows Mobile and patients can be offered a range of phones. In the European solution, Java technology was selected for reasons of portability and platform independence, so in theory the system can be implemented on any mobile platform capable of running JVM and RMI. There may be some cost in terms of overhead associated with running non-native code.

B. *Acceptance*

Clinicians found the European system presents clinical information of diagnostic quality and both patients and clinicians saw the utility of the telemedicine services, providing the system was stable. Beyond this, evaluation results are specific to clinical settings and space does not permit review here. Detailed evaluation results are available for all trials at the project websites.

The Australian trials showed that, for acceptance by patients and health professionals, it was important for the system to be useful, easy to use and personalised. Reliability and accuracy were essential for professional acceptance. CRM patients found that the PHM helped them to obtain a better diagnosis of their chronic condition. Some patients would have liked to have kept the PHM since it gave them peace of mind.

The cardiologists confirmed that the data was of sufficient quality to identify the main arrhythmias and pauses. They found the PHM very useful for a category of patients who do not get symptoms during their visit to the specialist, and for people who faint for no apparent reason (syncope). Thanks to the recordings, they can for example find out the cause of the

fainting and its duration. The cardiologist also makes a better impression on his patients suffering from chronic conditions. Instead of saying 'sorry, I suspect you have this but I cannot confirm it without evidence' he can refer to the PHM trials and say: 'use this and try and record the event'.

The patients who used the PHM to monitor their wellbeing found it useful to be in charge of their health and keep track of their progress (e.g. they can work out what triggers changes in blood pressure). CRM patients found the PHM far less intrusive and more practical than the Holter monitor. During the trials the PHM back end was specialised to suit the requirements of a cardiologist (he can annotate ECGs, print reports etc.). This makes PHM a useful tool for cardiologists.

Each user has different needs and preferences so it is important for the applications to be tailorable to patients' and health professionals' needs and requirements. The PHM trials highlighted that feedback not only depends on the clinical application but also on patient preferences. Some patients want to be in charge of their health, are aware of medical terminology and wish to get immediate feedback. Others prefer to use the application without any interaction because they do not wish to know what is happening as they find it stressful. Elderly patients living alone want audio reminders and warnings. Active people want the application to be as unobtrusive as possible. The flexibility of the PHM user interface allows personalisation of feedback to the user.

Overall, we can say that the MobiHealth system, which has been in development for longer than the PHM, is a complex but generic distributed system mediating between patients and healthcare organisations and designed for provision of a wide range of telemedicine services. The PHM system was originally focussed on a specific application relating to patient self-care, but is extending by evolutionary development both vertically (additional applications) and horizontally (by developing the clinical back end).

In the introduction we identified some dimensions whereby m-health services may be classified. MobiHealth focussed on physician care and remote processing whereas PHM focussed on patient self-care and local processing. PHM deals with monitoring, the latest MobiHealth BAN in Myotel with monitoring and treatment. PHM tended initially toward patient interaction and MH to transparent services at the patient's end. PHM began with acute applications whilst MH targeted both acute and chronic care.

This article shows that the two teams are applying different design and technology choices, and addressing different focal points (telemedicine versus personal health management). Despite the differences in technologies and approach to generic m-health service provision, the two systems however are converging in relation to most of the identified dimensions.

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MobiHealth system is currently under commercial development by MobiHealth BV.

The Personal Health Monitor is supported by the University of Technology, Sydney and is currently under commercial development.

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