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A framework for the comparison of mobile patient monitoring systems

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ABSTRACT

A *mobile patient monitoring system* makes use of mobile computing and wireless communication technologies for continuous or periodic measurement and analysis of biosignals of a mobile patient. In a number of trials these systems have demonstrated their user-friendliness, convenience and effectiveness for both patients and healthcare professionals.

In this paper we propose a generic architecture, associated terminology and a classificatory framework for comparing mobile patient monitoring systems. We then apply this comparison framework to classify six mobile patient monitoring systems selected according to the following criteria: use of diverse mobile communication techniques, evidence of practical trials and availability of sufficient published scientific information. We also show how to use this framework to determine feature sets of prospective real-time mobile patient monitoring systems using the example of epilepsy monitoring.

This paper is aimed at both healthcare professionals and computer professionals. For healthcare professionals, this paper provides a general understanding of technical aspects of the mobile patient monitoring systems and highlights a number of issues implied by the use of these systems. The proposed framework for comparing mobile patient monitoring systems can be used by healthcare professionals to determine feature sets of prospective mobile patient monitoring systems to address particular healthcare related needs. Computer professionals are expected to benefit by gaining an understanding of the latest developments in the important emerging application area of mobile patient monitoring systems.

1. Introduction

Electronic Health (e-Health) has been with us for many years and has been defined as the use of *Information and Communication Technology* (ICT) in the healthcare sector. With the emergence of mobile communications and advanced networking technologies, a specific field within e-Health, namely *Mobile Health* (m-Health), has emerged. *Mobile patient monitoring* is one of the m-Health services for the continuous or periodic measurement and analysis of a mobile patient's biosignals. The physiological signals that can be (continuously or periodically) measured and monitored from living beings are referred to as biosignals. Some of the biosignals commonly measured are *ElectroEncephaloGram* (EEG), *MagnetoEncephaloGram* (MEG), *Galvanic Skin Response* (GSR) and *ElectroCardioGram* (ECG). Many other parameters, such as *Heart Rate Variability* (HRV), can be calculated from (derived from) measured biosignals.

The scientific literature reports on a number of mobile patient monitoring systems. In this survey we present a comparative study of six patient monitoring systems selected according to the following criteria: use of diverse wireless communication techniques; evidence of practical trials; and availability of sufficient published scientific information. We have developed a comparison framework based on a generic architecture and associated terminology describing mobile patient monitoring systems, in turn based on the framework presented in [1].

In Section 1.1, we introduce terms related to ICT in healthcare and identify the position of mobile patient monitoring within the e-Health domain. Section 2 presents our generic architecture and terminology relating to mobile patient monitoring systems. A summary of each of the selected patient monitoring systems appears in Section 3. The use of proposed framework to elicit feature sets of a prospective real-time mobile patient monitoring systems and conclusions are presented in Section 4.

1.1. The position of mobile patient monitoring within ICT in healthcare

The scope of ICT as defined by the World Bank [2] covers hardware, software, networks, and media for the collection, storage, processing, transmission and presentation of information (voice, data, text, images), as well as related services. One application domain where ICT is applied is *E-Health*. According to a systematic survey of e-Health definitions [3], the most popular and comprehensive definition of e-Health is that of Eysenbach [4]:

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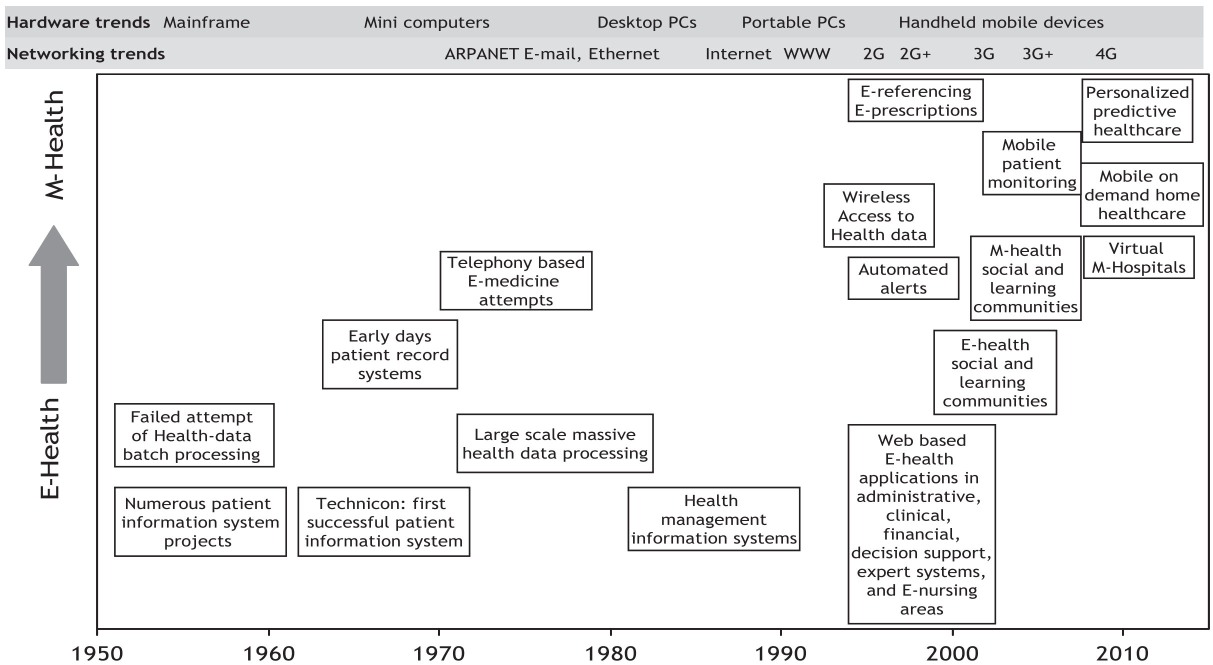

Fig. 1. Evolution from e-Health to m-Health (the information represented in this figure is based on description of e-Health history presented in [5]).

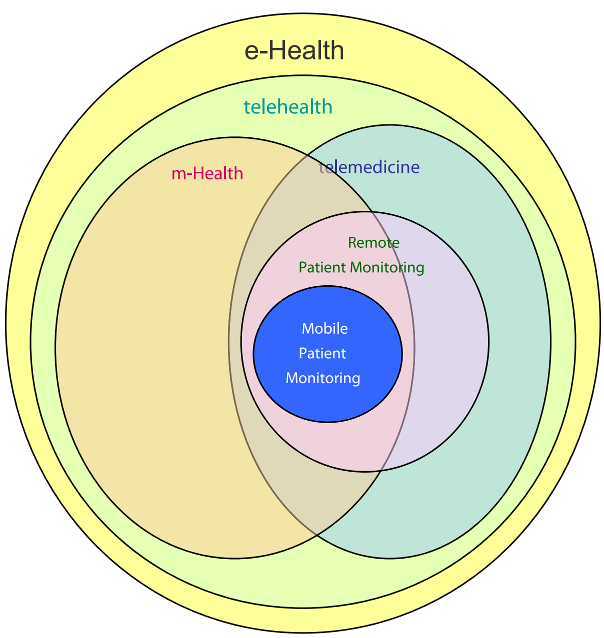

Fig. 2. Relationship between mobile patient monitoring and other e-Health paradigms.

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

From the above definition, it is clear that in the e-Health domain, ICT is being used for enhancing and delivering health services and related information. The delivery of healthcare mediated by e-Health systems should not have any adverse, negative, harmful or disadvantageous effects.

Another commonly used term in the healthcare sector is *telemedicine*. *Tele*, Greek for "at a distance", prefixing *medicine*, yields the meaning *medicine at a distance*. A more elaborate definition of telemedicine is provided by the Department of Essential Health Technologies of the World Health Organization [6]:

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

From this definition, it is clear that telemedicine is included in e-Health, but e-Health does not necessarily involve the aspect of remoteness. Both the European Space Agency Telemedicine Alliance and the American Telemedicine Association comment that *telehealth* has a broader meaning than telemedicine, however is still restricted in scope compared to the more general concept of e-Health. In addition to telemedicine, telehealth also encompasses educational, research, and administrative uses as well as clinical applications that involve nurses, psychologists, administrators, and other non-physicians [7].

In his article entitled 'E-Health Prospects' [8], Joseph Tan argues that because of the transition and transformation of traditional ICT applications to wireless platforms the emergence of *Mobile Health* (m-Health) is a natural development. Along with the ability to conduct traditional e-Health tasks such as viewing patient records or transmitting prescriptions to pharmacies on a mobile device, the new capability added to the e-Health domain by mobile technologies is that of exploiting immediate presence of mobile devices with the patient to acquire and deliver health related information. Fig. 1 shows chronological evolution from e-Health applications to m-Health applications. Typical m-Health applications are *automated patient alerts*, *e-prescriptions* and *mobile patient monitoring and tracking* [5].

As with the term e-Health, a number of definitions of m-Health exist. One of the most popularly cited is by Istepanian et al. [9]:

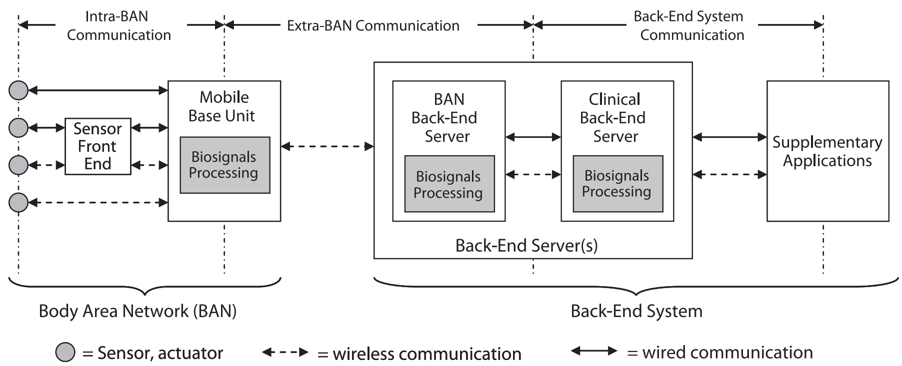

Fig. 3. A generic architecture of mobile patient monitoring systems.

Table 1
Parameters for comparison of mobile patient monitoring systems.

Parameter	Description
Architecture	Architecture of a mobile patient monitoring system according to the generic architecture shown in Fig. 3
Sensor/actuator set	Types of sensors/actuators/other BAN devices used
Sensor front end	Details of the sensor front end in terms of its make/model, included features and supported biosignal processing functions
MBU	Features of the MBU, in terms of supported applications, network interfaces and biosignal processing functions
Intra-BAN communication	• Communication type (wired/wireless) for communication between BAN devices and MBU • Biosignal processing along the communication path and on the MBU • QoS requirements for biosignal transfer • Communication protocol used for biosignal transfer
Extra-BAN communication	• Communication techniques for communication between MBU and BESys • Biosignal processing along the communication path and on the BESys • QoS requirements for biosignal transfer • Communication protocol used for biosignal transfer
BAN Back-End server and supplementary applications	• BAN Back-End server information such as technology choices for its implementation and deployment • Supplementary applications which use biosignal and other health related data available at the BAN Back-End server
Clinical Back-End server and supplementary applications	• Clinical Back-End server information such as technology choices for its implementation and deployment • Supplementary applications which use biosignal and other health related data available at the clinical Back-End server
Back-End System communication	• Mechanisms for making data generated at the Back-End servers available to the supplementary applications • Communication protocols and technology choices for data transfer
Trial patient group	Target patient groups which are intended to be monitored by a mobile patient monitoring system
Trial information	Information about trials conducted to validate a mobile patient monitoring system with a focus on the number of patients and duration of the trial
Reported findings/problems	Information about significant technical findings and problems reported during the trial

M-Health can be defined as the emerging mobile communications and network technologies for healthcare systems.

However, this definition focuses more on *mobile computing* as compared to *mobility of persons* involved in the healthcare system. We propose a definition of m-Health as:

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

In this definition, we stress the mobility of the patient within the healthcare system. The patient is a person who is receiving medical care. Of course mobility of health professionals may also be facilitated by m-Health systems, but we see patient mobility as essential to the concept of m-Health.

The Medical Dictionary Online defines *patient monitoring* as the continuous or frequent periodic measurement of physiological processes such as blood pressure, heart rate or respiration rate of a patient. There exist a variety of terms for the use of ICT in patient monitoring, e.g. *telemonitoring*, *remote patient monitoring*, *wireless patient monitoring* and *mobile patient monitoring*.

The American Telemedicine Association defines *telemonitoring* as the process of using audio, video and other telecommunications and electronic information processing technologies to monitor the health status of a patient from a distance. In the context of healthcare, the terms telemonitoring and remote patient monitoring are synonymous [10]. In the current state of telemonitoring [10] it is pointed out that apart from monitoring people who are ill (patients), telemonitoring may also refer to health monitoring of healthy individuals such as athletes or astronauts.

We consider mobile patient monitoring to be a subclass of remote patient monitoring, since with the latter all the associated healthcare tasks could be conducted solely using wired communication links (thereby possibly restricting movements of the patient). For instance the digital electrocardiogram (ECG) system described in [11] transmits a patient's ECG to a remote cardiologist using a fixed phone line modem, hence this is classed as remote patient monitoring but not as mobile patient monitoring. In this case the system enables home-based monitoring for example but not monitoring of the mobile patient at any arbitrary time and place. During mobile patient monitoring however, the patient is able to move freely anywhere inside or outside the home. Hence we define mobile patient monitoring as follows:

Mobile patient monitoring is the continuous or periodic measurement and analysis of a mobile patient's biosignals from a distance by employing mobile computing, wireless communications and networking technologies.

Wireless networking technologies, essential for monitoring the mobile patient, can be broadly categorized as: (1) Wireless wide area network (WWAN) technologies which provide low-bandwidth and high-latency service over a wide geographic area; and

(2) Wireless local area network (WLAN) technologies (e.g. WiFi) which offer a high-bandwidth and low-latency service over a narrow geographic area [12]. Experiments with mobile monitoring showed that second generation (2G) mobile phone technology such as GSM could support some mobile monitoring applications with relatively low bandwidth requirements. Development of 2.5G wireless networking technologies (e.g. GPRS), brought increased bandwidth, and later developments in 3G (eg UMTS) and more recently 4G brought ever higher data rates with WWAN technology. Long Term Evolution (LTE) for example promises data rates of 100 Mbps downlink and 50 Mbps uplink. Each increase in bandwidth (and hence achievable data rates) opens up new possibilities for more data-intensive mobile monitoring applications.

The relationship between the terms introduced in the foregoing and the position of mobile patient monitoring in relation to them is visualized in Fig. 2.

The scientific literature abounds with reports on m-Health systems focusing on mobile patient monitoring. A brief overview of m-Health systems and the potential benefits it brings is presented in [13], where a few successful case studies in the areas of *electronic patient records*, *emergency telemedicine*, *tele-radiology* and *home monitoring* are discussed.

An overview of m-Health systems for handling emergency situations and providing emergency services is found in [14] which describes a number of projects related to emergency health services and presents an extensive classification of these systems based on the wireless network technologies chosen for transmission of biosignals. In a comprehensive survey on the use of ubiquitous computing for remote cardiac patient monitoring [15]; a number of wireless cardiac monitoring systems are discussed with a focus on the architecture and QoS characteristics of the underlying platforms. An extensive survey of recent developments in the m-Health domain is given in [9].

2. Methods

2.1. A generic architecture for mobile patient monitoring systems

The architecture for mobile patient monitoring systems presented herewith is primarily based on the architecture of the mobile patient monitoring system developed during the MobiHealth project [1,16–18]. Fig. 3 shows the extended architecture, which we have generalized to accommodate the mobile patient monitoring systems described in [17,19–23].

In this architecture, a mobile patient monitoring system is seen as a set of *Body Area Networks* (BANs) and a *Back-End System* (BESys). Our definition of a BAN, adapted from [16,28], is a network of communicating devices worn on, around or within the body which is used to acquire health related data and to provide mobile health services to the user. A BAN consists of a *Mobile Base Unit* (MBU) and a set of BAN devices [18]. The MBU is a generic concept;

Table 2
Features of the Yale-NASA mobile patient monitoring system.

Parameter	Description
Sensor/actuator set	• Non-invasive sensors for measuring heart rate, 3-lead ECG, body surface temperature monitor, core body temperature pill • Accelerometer (for gross body motion and activity) • GPS system for position tracking
Sensor front end	• A central processing hub with RF capabilities and supporting maximum of 16 sensors per person • Is capable of storing and forwarding biosignal data • Biosignal data is transformed and encoded into ASCII format
MBU	RF transmitter
Intra-BAN communication	• *Sensor to SFE*: Personal Wireless local area network with digital RF signals, sensors queried 4 times per minute, SFE stores data for 5-min before transmission to MBU • *SFE to MBU*: RF communication
Extra-BAN communication	• RF 918 MHz link with one repeater station to facilitate vectored path for the RF signal transfer • Max *115 kbps* bandwidth • Biosignals bandwidth requirement: *2.4 kbps*
BAN Back-End server and supplementary applications	• Laptop at the Mt. Everest base camp • Aggregates received ASCII datasets every 5 min • Features GUI for display of biosignals
Clinical Back-End server and supplementary applications	• Server at the Yale university • Biosignal monitoring • Features GUI for biosignal display
Back-End System communication	• 64 kbps satellite Internet link – *2.4 kbps* used • *TCP/IP protocol* for the transfer of ASCII data
Trial patient group	High altitude climbers
Trial information	• Real-time monitoring of 3 climbers • Duration > 45 minutes
Reported findings/problems	• 95–100% sensors functioning • Rate of biosignal transmission loss from 3% to 12% • No biosignals were lost for more than 35 minutes or seven serial recordings. • No biosignals were lost for more than 20 minutes or 4 consecutive recordings

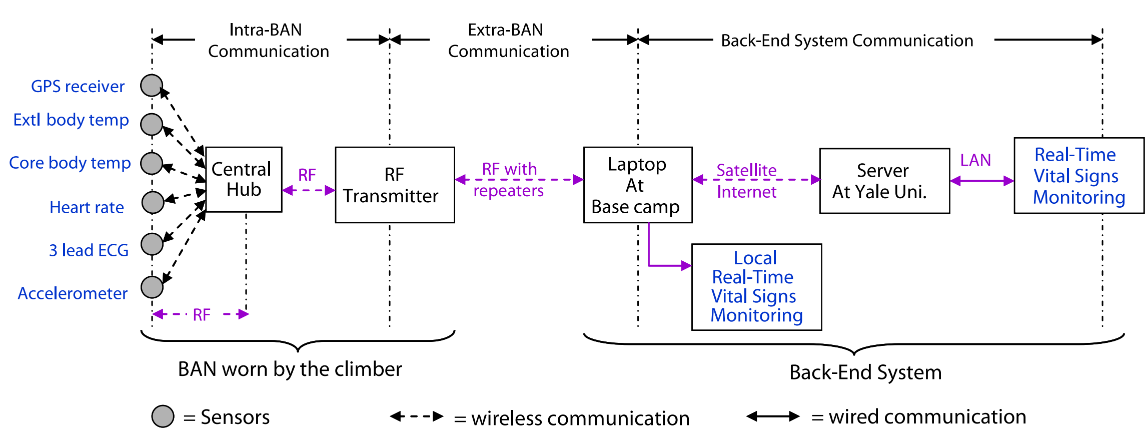

Fig. 4. Architecture of the Yale-NASA mobile patient monitoring system.

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typically the MBU functions (processing, storage and communications gateway) are implemented on a PDA or smartphone. BAN devices may be sensors, actuators or other wearable devices used for medical purposes. We distinguish between two types of BAN devices: *invasive* and *non-invasive*. Invasive devices are inserted in the living body by incision or by insertion of some instrument, while non-invasive devices do not infiltrate the body and do not involve any invasive medical procedure. Communication between the entities comprising the BAN is referred to as *Intra-BAN communication* and may be wired, wireless or a mixture of the two. Some sensors can directly transmit biosignal data to the MBU whilst others require an intermediate data acquisition device, a so called *Sensor Front-End* (SFE) connected to the MBU via a wired or wireless link. The SFE digitizes and filters raw analog biosignals before transmitting them to the MBU.

In the MobiHealth architecture, communication between the BAN and the BAN server, known as the Back End System (BESys), is referred to as *extra-BAN communication*. In line with the definition of mobile patient monitoring presented in Section 1, extra-BAN communication should be supported by a wireless link. The MBU acts as a communication gateway for the transmission of biosignals and other data between the BAN and the remote user (e.g. a hospital or health professional), via the BESys. The biosignals may be processed locally within the BAN and/or remotely in the BESys. One BESys supports multiple monitored patients, i.e. multiple BANs are served by one BESys [24]. The BESys comprises the *Back-End Server(s)* and supplementary applications whose functions include processing biosignals and other data received by the servers. We distinguish the *BAN Back-End* to which the MBU transmits biosignals data from the *Clinical Back-End* [1]. However the BAN Back-End and the Clinical Back-End may be collocated. Communication within the elements of the BESys is referred as *Back-End System communication*. Based on the generic architecture shown in Fig. 3, and the comparison framework of Jones et al. [1], we derived the parameters shown in Table 1 to compare selected mobile patient monitoring systems.

3. Results

3.1. Overview of selected mobile patient monitoring systems

A large number of mobile patient monitoring systems are reported in the literature. From these we selected a representative selection for comparison. The selection criteria used were: wireless communication technologies used, evidence of the practical trials and availability of sufficient published scientific information to gather comparison data. Based on these criteria, we selected the following mobile patient monitoring systems:

(1) Yale-NASA Himalayan climbers monitoring system developed by NASA and Yale university (hereafter referred as *Yale-NASA system*) [19].
(2) The Advanced Health and Disaster Aid Network (AID-N) system developed collaboratively by a number of institutions including John Hopkins University, University of California, Harvard University and others (hereafter referred as *AID-N system*) [20].
(3) Personalized Health Monitoring (PHM) system developed by the University of Technology Sydney (hereafter referred *as PHM system*) [21].
(4) A wireless-PDA based physiological monitoring system developed at the National Taiwan University in cooperation of National Taiwan University Hospital (hereafter referred as *NTU system*) [22].
(5) A wireless continence management system for the patients suffering from dementia developed by the Institute for Infocomm Research, Singapore in cooperation with other partners (hereafter referred as *CMS System*) [23].
(6) MobiHealth patient monitoring system developed as a part of the MobiHealth project (supported by Commission of the European Union in the frame of the 5th research Framework under project number IST-2001-36006) and subsequent projects (hereafter referred as MH system) [1].

The subsequent sections give an overview of each of the selected systems in terms of the generic architecture and comparison framework outlined in Section 2. At the end of each sub-section, we also provide summary of significant challenges addressed and major contribution of the system to the area of mobile patient monitoring research.

3.1.1. Yale-NASA mobile patient monitoring system

The Yale–NASA team organized the *Everest Extreme Expeditions* (E3) for the spring Himalayan climbing seasons in the years 1998 and 1999. E3 was focused on two aspects: *humanitarian* (providing medical support) and *scientific* (conducting medical and technology research). One of the aims of E3 was to determine the reliability of mobile patient monitoring systems in extreme environments. Along with providing medical care for the *Everest Base Camp* community; the Yale-NASA team also performed real-time monitoring of the selected climbers. The architecture of Yale-NASA system is shown in Fig. 4. Table 2 shows number of features of the Yale-NASA system according to our comparison framework.

The novelty of the Yale-NASA system [19,25] is that this is the first reported mobile patient monitoring system in truly remote or hazardous conditions and at high altitude. The system proved to be robust, fault tolerant and easily monitored through the

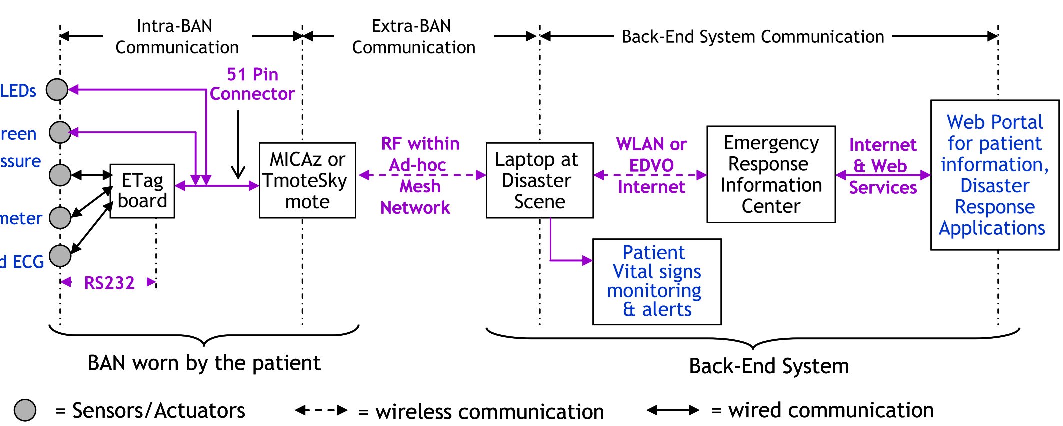

Fig. 5. Architecture of the AID-N mobile patient monitoring system.

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graphical interface. The biosignals are represented in raw ASCII data format. The rate of biosignal transmission loss ranged from 3% to 12%. However, no biosignals were lost for more than 35 min or seven serial recordings. In all proper functioning monitors, no signal was lost for more than four consecutive readings or 20 min. This occurred on only one occasion [25].

Such biosignal loss may have been caused by the severe weather conditions; however the effects of such conditions on the signal transmission were not determined. On several occasions there was a failure of signal acquisition (95–100% sensors functioning). However, frequent sampling (every 15 s) provided adequate compensation for momentary losses.

Since (bio)signals are needed to plot the general health and location of a patient, this exercise indicates that transmission modes such as low earth-orbiting satellites (LEOS) may prove effective to monitor people in remote areas. Use of LEOS helps to eliminate need for RF repeaters and support from numerous technicians.

3.1.2. AID-N mobile patient monitoring system

In medical emergencies where there are many casualties, such as major incidents or disasters, a critical first step in the emergency response is rapid and accurate triage of casualties. Triage refers to sorting of patients according to the urgency of their need for medical intervention. During emergency response, triage information needs to be communicated and continuously updated to multiple parties in the response team. The AID-N system tested during a mass casualty disaster drill [20] is proposed as an electronic alternative to traditional paper tag or colored ribbon based triage systems. In this drill exercise, the usability of the AID-N system was compared with the traditional paper tag based triage system. The architecture of the AID-N system is shown in Fig. 5. Table 3 shows number of features of the AID-N system according to our comparison framework.

It was found that use of the electronic AID-N system [22] allowed first responders to retriage patients three times as many times as first responders using paper tags. The AID-N approach then can increase quality and quantity of patient care during disaster situations. There were several challenges reported during the implementation and deployment of the AID-N system. Firstly, during the disaster situations, the requirement for indoor location tracking capability with a minimal setup time and a resolution of one meter accuracy were found to be challenging issues. Secondly, high data rate of ECG waveforms was found to cause serious delays while running several motes in parallel in an ad-hoc mesh network. Thirdly, technical challenges arose because casualties sometimes wandered in and out of the radio coverage area.

Table 3
Features of the AID-N mobile patient monitoring system.

Parameter	Description
Sensor/actuator set	• Non-invasive sensors for measuring heart rate, 2-lead ECG, pulse rate, oxygen saturation, blood pressure • LEDs signify triage class of the patient • LCD displays oxygen saturation and heart rate
Sensor front end	• Specially designed ETag sensor board • RS232 – DB9 connector for connecting sensors • Interfaced with MICAz mote with 51-pin expansion connector
MBU	• MICAz or Tmote Sky mote • Bulitin IEEE 802.15.4 radio transceiver • 51-pin expansion connector with D/A interface for connecting to the SFE • ECG amplification, filtering and sampling • Algorithm for extracting heart rate • Indoor radio range: 20–30 m • Outdoor radio range with substitute IEEE 802.11 antennas: 23-66 m
Intra-BAN communication	• *Sensor to SFE*: Serial communication using RS232 standard, BP readings every 5 min • *SFE to MBU*: Over the 51-pin connector • *MBU to Actuators*: LED management over 4-bit data bus • 128 bytes needed for ECG waveform
Extra-BAN communication	• Ad Hoc mesh network constituted by the MBUs using RF 2.4 GHz frequency based on the CodeBlue wireless sensor network • Spanning tree for each BAN back-end server covering all the assigned MBUs • Max *250 kbps* bandwidth • 1 byte needed for heart rate, 128 bytes for ECG waveform
BAN Back-End server and supplementary applications	• Laptop at the disaster scene • Vital signs analysis algorithms • Features GUI for vital signs and triage display • WLAN and EDVO PC card network interfaces
Clinical Back-End server and supplementary applications	• Central server known as *Emergency Response Information Center* • Information sharing with other systems like web portal • Web Services for providing patient and triage information • Coordination of response activities at the disaster site using PDAs
Back-End System communication	• WLAN connectivity preferred • Alternately, transfer over EDVO – CDMA 1x-data network
Trial patient group	"Patients" at a disaster scene (drill exercise)
Trial information	• 20 patients, one incident commander, treatment officer, transport officer, triage officer each, three response team members • Use of pulse oximeter, 2-lead ECG sensors and blood pressure sensor
Reported findings/problems	• High ECG data rate caused serious delays while running several motes in parallel • Coverage problems due to patients wandering out of range of other patients and line of site problems • Suitable mechanism for location tracking is needed

3.1.3. PHM mobile patient monitoring system

The Personal Health Monitor (PHM) system [21] is designed for patients who have a suspected cardiovascular disease and need to be monitored around the clock. The PHM system proposes use of off-the-shelf sensor systems which incorporate a built-in sensor front end. This approach allows a PHM system user to use their own mobile phone running Microsoft Windows and to buy or rent the required sensors. The patient downloads the PHM application onto the mobile phone and uses it like any other mobile application. The architecture of PHM system is shown in Fig. 6. Table 4 describes the PHM system according to our comparison framework.

According to the article [21] the PHM trial demonstrated that the system is easy to use and, in the majority of cases, biosignals received by the cardiologists were of sufficient quality to make a proper assessment. Another feature of the PHM system is that the healthcare professional can select one or more sensors to be used for a particular patient for providing personalized monitoring and treatment. The PHM trials highlighted the need for personalized feedback. Findings were, for example, that some patients did not like to interact much with the application as they found it stressful. Some elderly patients living alone reported that they would have liked to have audio reminders and warnings.

Further feasibility study of the use of PHM system for a non-invasive *Cardiac Rhythm Management* (CRM) *System* is reported in [26]. Accordingly, to date, this system has been applied on 70 low risk heart patients and the preliminary results show the

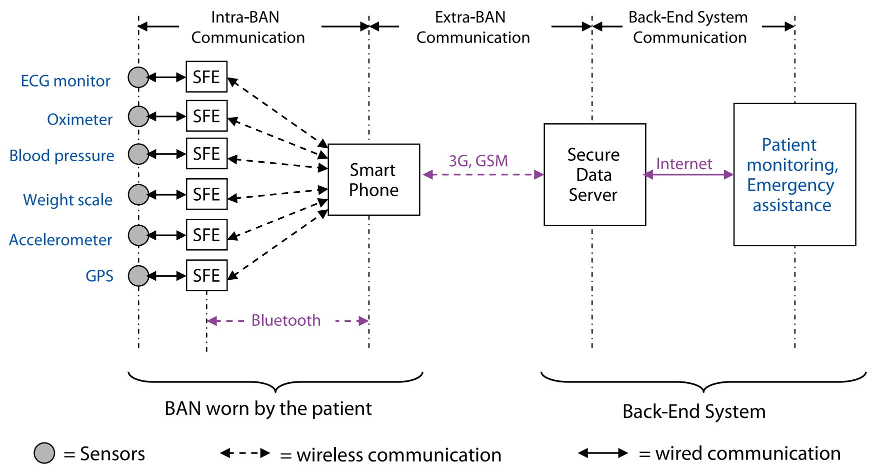

Fig. 6. Architecture of the PHM mobile patient monitoring system.

Table 4
Features of the PHM mobile patient monitoring system.

Parameter	Description
Sensor set	• Off-the-shelf non-invasive sensor systems • 1 channel ECG monitor, pulse oximeter, blood pressure, weight scale, internal/external GPS, accelerometer • All external sensors with Bluetooth capabilities
Sensor front end	• Subcomponent of off-the-shelf sensor system incorporating embedded software for signal processing
MBU	• Any smartphone running Microsoft Windows Mobile OS • Smartphone application incorporating biosignal analysis algorithms
Intra-BAN communication	• *Sensor to SFE*: custom wired communication • *SFE to MBU*: Bluetooth
Extra-BAN communication	• Internet connection using 3G or GSM technologies
BAN Back-End server and supplementary applications	• Microsoft ASP .NET based server • Features GUI for biosignals display • Biosignals processing and storage
Clinical Back-End server and supplementary applications	• Patient monitoring and emergency services
Back-End System communication	• Secured Internet connection
Trial patient group	Patients suffering from cardio-vascular disease
Trial information	• 70 patients with low-medium risk
Reported findings/problems	• PHM BAN and application are easy for patients to use • The data received by the healthcare professionals is of sufficient quality to diagnose cardiovascular problems

commercial potential of this system for identifying and diagnosing arrhythmia abnormalities. The results of this study [26] are used to identify potential applications of the PHM system in the following areas: *cardiac rehabilitation*, *community healthcare*, *monitoring of lifestyle changes* and *athletic performance*.

3.1.4. CMS mobile patient monitoring system

Incontinence refers to the inability to control or manage voluntarily the process of urination or defecation. It is highly prevalent in the elderly, especially in those suffering from dementia. The CMS system [23] is targeted at elderly dementia patients residing in nursing homes and suffering from incontinence. The BAN consists of receiver(s) associated with a wetness detection sensor integrated into the MICAz mote platform mounted near the patient's bed or wheel chair. In order to detect incontinence, the wetness sensor is inserted into the diaper which is worn by the patient all the time. The architecture of the CMS system is shown in Fig. 7. Table 5 shows the features of the CMS mobile patient monitoring system.

The CMS system [23] involves the use of a scalable and extensible distributed sensor network to support potentially large deployment of wetness sensors in institutions such as nursing homes, elderly care centers, etc. With the use of wireless sensor networks, incontinence monitoring of the elderly can be performed either on the bed (inside the ward) or on the wheelchair (outside of the ward). The relay mechanism used for the transfer of patient's biosignals means that patients are free to move around in the nursing home. During the trial of the CMS system no false alarms were reported, however the wetness detection ratio was only 50%. This low ratio was attributed to various causes, identified as: deliberately reduced sensitivity of the wetness sensor for eliminating false alarms, wrong placement of the sensor within a diaper and variable absorbance properties of different types of diapers. The trial also highlighted the RF out-of-coverage problems and the need for training caregivers to properly handle day to day system operations.

3.1.5. NTU mobile patient monitoring system

Transport of patients within hospitals (e.g. to the ICU, or to the radiology room) often involves the transportation of bulky medical monitoring equipments along with the patient's trolley. These bulky monitors and wires connecting them to sensor leads could result in problematic situations as well as inconvenience. The NTU system [22] is designed as an alternative to the use of bulky medical monitoring equipment during intra-hospital patient transport by making use of advanced mobile technologies for continuous patient monitoring. Along with the use of TCP/IP for error-free biosignal transmission, the NTU system includes robust security features such as user authentication, secure wireless transmission and use of an end-to-end *Advanced Encryption Standard* (AES) algorithm. The architecture of the NTU system is shown in the Fig. 8. Table 6 shows the features of the NTU system according to the comparison framework.

The distinguishing aspects claimed of the NTU system [22] are that it improves the portability of patient monitoring equipment during intra-hospital transport of the patients and wireless connectivity increases flexibility and usability of patient monitoring. The NTU system was found to be user-friendly, convenient and

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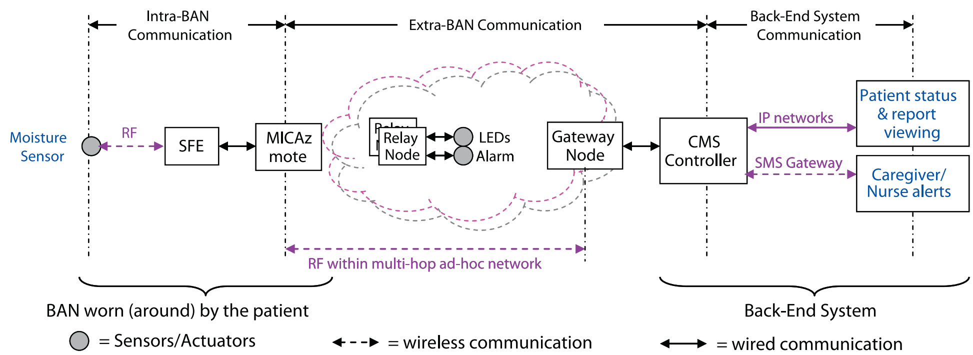

Fig. 7. Architecture of the CMS mobile patient monitoring system.

Table 5
Features of the CMS mobile patient monitoring system.

Parameter	Description
Sensor/actuator set	• Commercially available wetness detection sensor with RF communication capabilities • Actuators consists of LEDs and alarm for notification on detection of the wetness caused by either urine or feces • Actuators are integrated into so called *relay nodes*
Sensor front end	• Subcomponent of the wetness sensor system, especially RF receiver incorporating embedded software for signal processing • Wetness sensor unit only sends one-time moisture detection signal to the SFE upon occurrence of wetness
MBU	• MICAz mote with 2.4 GHz RF communication capability – so called *sensor node*
IntraBAN communication	• *Sensor to SFE*: proprietary RF wireless communication • *SFE to MBU*: custom wired communication through a digital hardware interfacing bus such as ADC, I2C, SPI, etc.
ExtraBAN communication	• Multi-hop wireless network using RF communication • Consists of relay cum actuator nodes and gateway node • MBU, *relay nodes* and *gateway node* communicate with each other wirelessly • Gateway node has wired connectivity such as Ethernet, Serial, etc to the Back-End server
BAN Back-End server and supplementary applications	• *CMSController* incorporating Java based *Service Oriented Architecture* (SOA) modules • Caregiver/nurse SMS alerting through mobile phone via SMS gateway
Clinical Back-End server and supplementary applications	• Patient status monitoring and report viewing over the IP network
Back-End System communication	• Based on the principles of SOA • SMS gateway • IP network
Trial patient group	Elderly patients suffering from dementia and incontinence and wearing diaper all the time
Trial information	• Prototype trial with 1 patient over 2 weeks • In a nursing home • 2 relay nodes, 1 sensor node and 1 gateway node
Reported findings/problems	• No false alarms • Wetness detection rate of 50% attributed to deliberately reduced sensitivity of the moisture sensor, position of the sensor within the diaper and variable properties of different types of diapers • RF out-of-range problems due to the patient wandering out of range of the sensor node

feasible for intra-hospital patient transport. Improvements proposed for the NTU system included use of advanced algorithms for determining many health-related parameters using only a few sensors and replacement of the RS232 connection by Bluetooth for additional flexibility.

3.1.6. MH mobile patient monitoring system

The main motivation behind the development of the MobiHealth (MH) system, first developed during the MobiHealth project, was that of providing ubiquitous medical care by means of mobile monitoring using Body Area Networks and wireless technology. MobiHealth was the first project to apply Body Area Network Technology for patient monitoring applications, hence was the originator of the concept of Health BAN [1,17,18]. The system was further developed in various European and Dutch projects [27,28]. Instead of focusing on patients with one particular health condition, MH focused on developing a generic BAN which can be specialized for any particular type of telemonitoring or teletreatment application by integrating a specific set of sensors and other devices together with the appropriate application functionality. During the MobiHealth project the generic BAN was specialized for different conditions including high-risk pregnancies, trauma, cardio-vascular disease and COPD [29]. The original MH BAN was implemented using both wired (front-end supported) sensors from TMSI and wireless (self-supporting) sensors from EISlab [30]. In both cases Bluetooth was used for intra-BAN communication [18]. The architecture of the MH system is shown in Fig. 9. Table 7 shows the features of the MH system according to the comparison framework.

The MobiHealth project trials reported positive experience working with the healthcare organizations and clinicians. However, in the initial version of MH system, technical failures (such as system instability), sub-optimal interface design and a difficult (re)start sequence caused irritation and confusion to users. Preliminary trials showed the feasibility of using the system, however a number of problems were encountered. For example, ambulatory patient monitoring was more successful for some biosignals than others, because in some cases measurements were severely disrupted by movement artefacts [17]. The limited bandwidth provided by 2.5G wireless wide area network (WWAN) technologies (GPRS) was not sufficient for the applications which required monitoring many simultaneous signals per user. Where 3G (UMTS) was available the MobiHealth trials did not suffer from this restriction. A later project, AWARENESS [31], implemented an epilepsy seizure detection application where, when available bandwidth is low, an analysis algorithm runs locally on the BAN and only alarms are sent to the health professional. However, if sufficient bandwidth is available, the biosignals are transmitted to the back-end for processing by a more sophisticated detection algorithm [28]. Results from the Myotel project [32] indicated that continuous local

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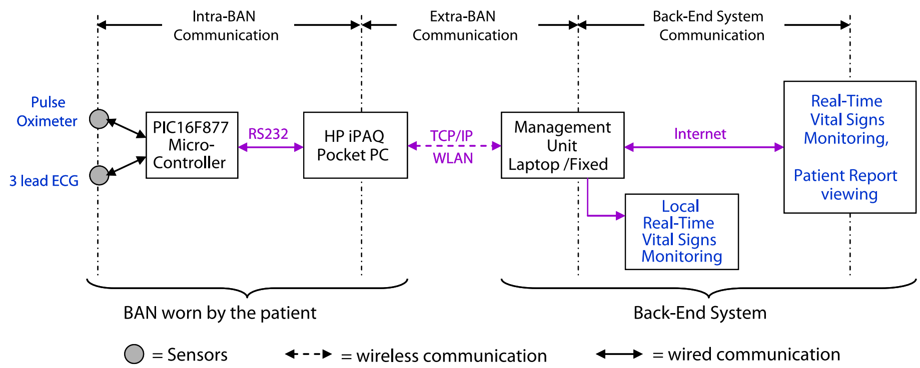

Fig. 8. Architecture of the NTU mobile patient monitoring system.

Table 6
Features of the NTU mobile patient monitoring system.

Parameter	Description
Sensor set	Non-invasive sensors for measuring 3-lead ECG and pulse-oximeter
Sensor front end	• Based on 8-bit PIC16F877 microcontroller • ECG signals amplification, filtering and AD conversion • Processing of *photoplethysmograph* (PPG) signals to obtain pulse rate and oxygen saturation • Digitization signals with 200 Hz sampling frequency
MBU	• HP iPAQ Pocket PC H5450 with integrated WLAN • System program developed in Microsoft embedded visual C++ to display real-time waveforms, local data storage and alarm triggering • Capable of storing biosignals in the SD memory
IntraBAN communication	• *Sensor to SFE*: wired communication • *SFE to MBU*: Serial communication using RS232 standards, baud rate of 115.2 kb/s.
ExtraBAN communication	Data transfer over TCP/IP using WLAN connectivity
BAN Back-End server and supplementary applications	• So called *Management Unit* • Laptop/fixed terminal running Windows 2000 OS and MySQL server • Biosignal display
Clinical Back-End server and supplementary applications	Vitals signs transmission and patient reports transfer over the Internet for interested clients
Back-End System communication	Internet connection using wired or wireless connectivity
Trial patient group	20 healthy patients at National Taiwan University Hospital
Trial information	• Trial run over 1 month, used by 30 doctors and 20 nurses • Transportation of patients from ICU to radiographic examination room
Reported findings/problems	• No errors reported in biosignal transmission • NTU system was rated as highly satisfactory • Outperforms traditional monitors system in terms of mobility and usability • No interference of NTU system detected with other electronic equipment used in ICU and radiographic examination

biofeedback enabled chronic pain patients to adapt their behavior rapidly and results in long lasting treatment effects. Adding a tele-treatment dimension with feedback from the remote therapist was shown to further improve clinical outcomes related to pain and disability [32].

4. Discussion

The following observations can be made based on analysis of the mobile patient monitoring systems presented in Section 3. These systems have been used in both outdoors and indoors environments. Most systems were reported to be user-friendly and convenient to use for both patients and healthcare professionals; however where there is system instability or technical problems this not surprisingly causes annoyance and reduces acceptance. The trials of these systems have in general shown feasibility and acceptance in day-to-day free living settings. During the trials, it was observed that mobile patient monitoring systems can reduce time to treatment. Some mobile patient monitoring systems are custom designed for a single clinical application whilst others are generic and can be adapted for different classes of patients and even potentially for patients suffering from multiple co-morbidities. The merits of mobile patient monitoring are supported in an independent study [33], which found that the use of mobile patient monitoring systems has the potential to reduce frequency and duration of hospitalization of patients suffering from heart failure.

Based on the number of features reported for individual mobile patient monitoring systems, Table 8 provides a classification of these systems according to a number of technical parameters. Since maximum mobility is supported by employing wireless communication technologies, we emphasize the wireless communication aspects of each selected system.

Supported number of sensors: The parameter relates to the range of sensors which have been integrated to this BAN. Please note: 'supported number of sensors' does not necessarily imply that all the sensors are used simultaneously in any application. Rather it may imply a range of applications each using a different subset of sensors. For instance, in the MH system a total of 10 sensors have been used to date in various tele-monitoring and tele-treatment applications but not all 10 in combination. In comparison, the CMS system uses a highly condition-specific wetness detection sensor in because it is designed for a highly specific application, namely incontinence management.

Sensor to SFE communication: Depending on whether intra-BAN communication is wired or wireless, the patient's freedom of movement can be affected, hence mode of Sensor to SFE communication is important to consider in relation to application requirements.

SFE to MBU communication: The SFE to MBU communication can also be wired or wireless. The advantage of using wireless SFE to MBU communication is that patient movements are least affected while performing activities such as driving a car.

Biosignal storage and display on the MBU: The ability of the MBU to display biosignals locally depends on the capabilities of a device that implements the MBU. A handheld mobile device (mobile

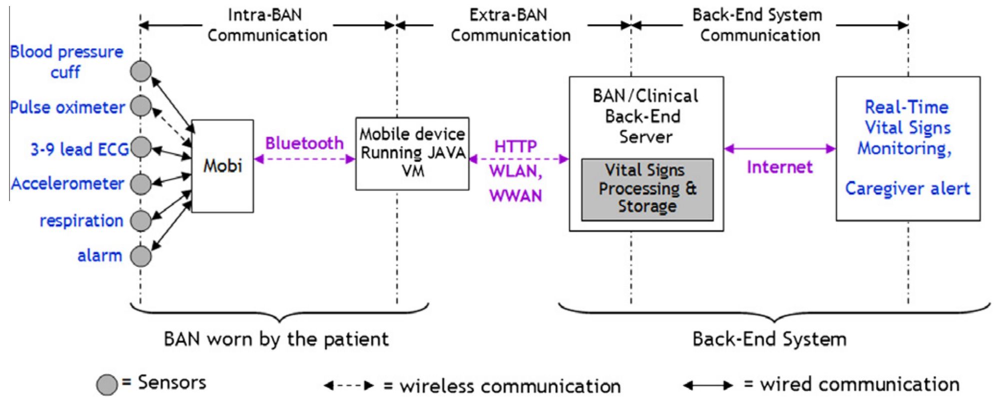

Fig. 9. Architecture of the MH mobile patient monitoring system.

phone or PDA) is a commonly used device which functions as the MBU. In addition, other types of wireless devices (e.g. wireless sensor node, RF transmitter) are also used as MBUs. In the systems where a handheld mobile device is used as the MBU, the biosignals can be displayed on the MBU as well as being stored locally on the MBU. The requirement to display biosignals locally is highly dependent on the specific clinical application and will affect decisions about which hardware platform to use. Assuming the device capability is there, the decision to display biosignals locally or not can also depend on individual patient/user preferences, as found in cardiac care during use of the PHM system [1], where some patients want to see feedback on their smartphone and others prefer the data to go silently to their physician without having to interact with the BAN themselves as they find that stressful. The biosignal storage facility on the MBU is essential for increasing system robustness in case of extra-BAN communications problems.

Intra-BAN communication: The information in Table 8 shows that no problems with intra-BAN communications were reported in the sources. However, it should be noted that in case intra-BAN communication is wireless, it requires application of wireless data security mechanisms for the protection of patient's biosignals and personal data.

Extra-BAN communication protocol and technology: In the systems where point-to-point or ad-hoc networks provide the extra-BAN connectivity, SMAC is the preferred communication protocol. In the systems where the extra-BAN connectivity is provided by WLAN or WWAN technologies, IP based communication protocols are used for biosignals delivery. In all of the systems presented here, whenever required, the biosignals are delivered continuously from the MBU to the back-end system. In terms of the QoS requirements, the bandwidth requirements for the biosignals delivery are explicitly stated in some of the systems [19,20,22,29], however delay and jitter requirements are not explicitly considered anywhere. During the trials of these systems, certain problems were reported. The wireless network problems refer to the lack of sufficient bandwidth for the transmission of signals, high delay and unavailability of the wireless network coverage. To solve these problems, in the research literature [35] the use of context-aware vertical handover techniques in mobile patient monitoring systems is proposed.

Intended geographic area of use: If positioning and/or location-based services are required by an m-Health application, being indoors or outdoors affects the location determination technology used. In an outdoor environment, GPS localization is a ubiquitously available technique to a precision of 10 meters or better; however, there are a few problems associated with using the GPS localization technique [36]. The main problem is that there is little or no indoor coverage of the satellite signals. To solve the problem of indoor localization, a number of approaches exist. A comprehensive survey and comparison of wireless indoor localization techniques and systems is provided in [37]. Accordingly, the techniques such as RSS-based WLAN localization which determine the current location within 1–5 m precision can be considered for use in mobile patient monitoring systems.

End-to-End security: Along with efforts to ensure that the QoS requirements for biosignals delivery are properly elicited and met by the extra-BAN communication path, it is also necessary to develop end-to-end security solutions for the transmission of biosignals. In these cases, the additional transmission delay resulting from the impact of user/network authentication needs to be taken into account. To make sure that the healthcare professionals have access to high quality biosignals and other BAN data, mechanisms to avoid data loss or corruption during transfer from the sensors to the clinical back-end are needed in these often safety critical healthcare systems.

BESys communication: The preferred technology choices for the communication within the components of the back-end system are service oriented architecture technologies and web based technologies.

4.1. Application of the proposed framework

Below we refer to a healthcare scenario from the Freeband AWARENESS project [31] to demonstrate that information of the type presented in Table 8 can be used by m-Health professionals and engineers as a basis for defining the feature sets required in a prospective mobile patient monitoring system being designed to address a particular health related need. This kind of situation usually occurs in the initial phases of the project such as requirements analysis. The following scenario is taken from [38] and it represents an event in the life of a fictional epilepsy patient.

"*Mr. Janssen is a 46-year-old man who suffers from epilepsy. Recently, Mr. Janssen has been wearing a 24-h seizure- monitoring system. Measuring on heart rate variability and physical activity, this system can predict future seizures and is able to contact relatives or health care professionals automatically. The aim of using this system is to provide Mr. Janssen with both higher levels of safety and independence in order that he may function more normally in society despite his seizures. Tonight, Mr. Janssen is driving his car because he planned to visit his daughter. Since he has been free of seizures for more than 1 year, he received approval from the Central Department for Driving Ability Certificates (In Dutch "Centraal Bureau voor Rijvaardigheidsbewijzen" CBR) for driving a car. Whilst he is driving along the highway, the 24-h monitoring system*

Table 7
Features of the MH mobile patient monitoring system.

Parameter	Description
Sensor set	• Any subset of 3, 4 and 9 channel ECG, surface EMG, pulse oximeter, respiration sensor, temperature sensor, activity sensors (step-counter, 3D accelerometer) • Any wearable sensor with a suitable communication interface can be integrated • GPS receiver
Sensor front end	• The "Mobi" SFE has 3/4/9-channel variants with inputs for ECG, 1 auxiliary (AUX) input for either an activity or a respiration sensor, marker/alarm button input, pulse-oximeter (SaO2) input. • Incorporates programmable DSP capable of performing bio-signal and other processing • Bluetooth serial port
MBU	• Implemented on various mobile phones and PDAs under different operating systems • Any mobile platform capable of running Java VM and RMI (Remote Method Invocation) • Bluetooth support • Application specific functionality and GUI running over generic BAN software layer and protocol stack. E.g. seizure detection algorithm for epilepsy.
IntraBAN communication	• *Sensor to SFE*: custom wired/wireless communication • *SFE to MBU*: Bluetooth
ExtraBAN communication	• GPRS, UMTS, HTTP connection using WLAN/WWAN technologies
BAN Back-End server and supplementary applications	• Server with Jini surrogate host, Jini lookup service • Database for biosignal storage (Jini Ban Data Repository) • Biosignals processing and display
Clinical Back-End server and supplementary applications	• Context-aware functionality for providing e.g. caregiver assistance in case of emergency
Back-End System communication	• Based on Java RMI principles • A generic m-Health portal acts as a Jini client to access biosignal data from the Back-end server and displays them for viewing by the physician or for further processing
Trial patient group	Low risk patients suffering from ventricular arrhythmia, women with normal pregnancies (representing high risk pregnancies), acute trauma patients, women with rheumatoid arthritis, mental health patients, patients with COPD, elderly with co-morbidities including COPD and epilepsy
Trial information	• 17 trial groups over 4 projects • Multi centre and multi-language international trials in Netherlands, Germany, Spain, Sweden and Cyprus
Reported findings/problems	• Technical failures such as system instability in the initial versions of MH system • Bandwidth problems and loss of network connectivity • Good acceptance from the end-users in the latest versions. E.g. continuous local biofeedback enables chronic pain patients to adapt their behavior rapidly and results in long lasting treatment effects

identifies the possible occurrence of a seizure within a couple of minutes. Immediately, the system alarms the central monitoring centre. In addition, if possible biosignals are sent over broadband. The system detects the high speed of Mr. Janssen moving from position A to position B and concludes that Mr. Janssen could be driving a car. Because of the dangerous situation, Mr. Janssen is warned of a possible seizure by the system directly, without the mediation of a doctor. Consequently, Mr. Janssen is able to stop his car at the side of the highway before the seizure occurs. Meanwhile, the doctor at the central monitoring centre decides to send a health team to Mr. Janssen as soon as possible, since there are no voluntary aid persons around to assist."

By analyzing such scenarios, the required features relating to the parameters of Table 8 can be determined, as illustrated below. (Scenario-based methods are useful for requirements elicitation but are not complete; the development and analysis of scenarios represents one part only of the requirements elicitation phase of design.)

Supported number of sensors: In the epilepsy scenario, the physiological parameters needed are: *heart rate variability* (HRV) and *physical activity levels* [34]. HRV can be derived from ECG and physical activity can be determined by accelerometry, hence electrodes for measuring ECG and an accelerometers are indicated as the required sensor set. Further analysis will be needed however to determine for example how many channels of ECG, and at what sampling rate, are needed to supply data of appropriate quality for the particular clinical application.

Sensor to SFE communication: For the epilepsy scenario, wireless intra-BAN communication is preferred so that the patient movement is not restricted.

Biosignals storage and display on the MBU: For the epilepsy scenario, it is necessary to store patient's biosignals locally on the MBU, so that HRV history data can be analyzed locally to detect/predict seizure. This also requires that the seizure detection/prediction algorithm [34] should be implemented on the MBU. Moreover, feedback (e.g. possible occurrence of a seizure) is to be provided to the patient locally; hence it is required to display the patient's condition on the MBU.

Intra-BAN communication: For the epilepsy scenario, mechanisms are needed to ensure that no biosignal data is lost during intra-BAN communication, so that accurate historic data can be mined which may lead to better detection or prediction of seizures.

Extra-BAN communication protocol and technology: For the epilepsy scenario, since the patient drives a car, WLAN or WWAN connectivity needs to be available along the patient mobility path and IP based communication protocol is a preferred protocol for biosignal delivery to the back-end system.

Intended geographic area of use: In the epilepsy scenario 24 h patient monitoring is envisioned. Hence, the patient monitoring system needs to be suitable for both indoor and outdoor settings. Similarly, a suitable location determination technology needs to be used, so that in case of detected seizure timely and appropriate assistance can be dispatched to the patient's location.

End-to-End security: The epilepsy scenario requires provision of end-to-end security and mechanisms to avoid data loss or corruption in order to safeguard patient's biosignals data during its transmission to the healthcare professional.

BESys communication: The most common functions provided by the back-end system are displaying patient's biosignals, viewing the patient report, providing emergency assistance to the patient and alerting the healthcare professional. This set of functions is also necessary to support monitoring of epileptic patients.

Given the epilepsy detection/prediction scenario and the characteristics of selected patient monitoring systems, the PHM system and MH system seem to be suitable candidates for monitoring epileptic patients. From the data in Table 8, it is observed that both of these systems are designed for use in indoor/outdoor environment. They support wireless communication from the SFE to MBU. Both systems display and store biosignals on the MBU. However, end-to-end security needs to be provisioned in both of these systems.

Table 8
Summary view of selected mobile patient monitoring systems Acronyms: BT – Bluetooth, RF – Radio Frequency.

Parameter	Yale-NASA	AID-N	PHM	CMS	NTU	MH
1. Supported number of sensors	5	3	>6	1	2	>10
2. Sensors to SFE communication	RF	Wired	Wired	RF	Wired	Wired
3. SFE to MBU communication	RF	Serial	BT	Wired	Serial	BT
4. Biosignals display on the MBU	No	Yes	Yes	No	Yes	Yes
5. Biosignals storage on the MBU	No	No	Yes	No	Yes	Yes
6. Intra-BAN comm. problems	No	No	No	No	No	No
7. Extra-BAN comm. problems	No	Yes	No	Yes	No	Yes
8. Extra-BAN communication technology	RF	Multi-hop ad-hoc	3G, GSM	Multi-hop ad-hoc	WLAN	WLAN, 3G, GPRS
9. Extra-BAN comm. protocol	SMAC	SMAC	TCP/IP	SMAC	TCP/IP	HTTP
10. BESys communication technology	TCP/IP	Web services	Web services	IP	HTTP	Jini
11. Intended geographic area for use	Outdoor	Indoor	Indoor/outdoor	Indoor	Indoor	Indoor/outdoor
12. End-to-End security	No	No	No	No	Yes	No
13. Reported trial problems	Yes	Yes	No	Yes	No	Yes

4.2. Conclusions and future direction

In this paper we proposed a generic architecture, associated terminology and a classificatory framework for mobile patient monitoring systems. The proposed framework is applied to classify six mobile patient monitoring systems from the literature. Most of the systems were reported to be user-friendly and convenient to use for both patients and healthcare professionals; however where there is system instability or technical problems this not surprisingly causes annoyance and reduces acceptance. The main problems/observations are summarized as follows: (1) Reported wireless network problems are related to the lack of sufficient bandwidth for transmitting biosignals, high delay and unavailability of wireless network coverage. (2) QoS requirements are highly (clinical) application-specific. The bandwidth requirements needed to achieve the required biosignals delivery rate and quality are explicitly stated in some of the articles, however network delay and jitter requirements also need to be determined for critical healthcare applications. (3) Most of the surveyed mobile patient monitoring systems lack necessary solutions to ensure end-to-end security of biosignals data. (4) The mechanisms to eliminate loss of biosignals during their transfer from the sensors to the back-end system are necessary, so that the healthcare professionals have access to high quality biosignals.

We also showed an application of this framework to determine feature sets of prospective real-time mobile patient monitoring systems using the example of epilepsy monitoring. Based on scenario analysis, it is concluded that the *Personalized Health Monitoring* (PHM) *system* [21] and *MobiHealth system* [1] seem to be suitable candidates for monitoring epileptic patients out of the selected six systems.

There is an emerging paradigm of using *Mobile Virtual Communities for TeleMedicine* (MVC4TM). In a virtual community, a group of people interact with each other around some common or shared interest, problem or task. If the community members interact with each other independent of the location and time using mobile devices and wireless communication technologies, such a community is referred to as a mobile virtual community [39]. In the telemedicine domain, the MVC4TM research is exploring the possibilities of contributing to meeting the social demands and needs of patients as well as empowering them psychologically to encourage their self-management. Considering this bigger picture, it is of enormous value to integrate future mobile patient monitoring systems with MVCs in telemedicine.

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