22 FROM TELEMEDICINE TO UBIQUITOUS M-HEALTH: THE EVOLUTION OF E-HEALTH SYSTEMS

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22.1 INTRODUCTION

Existing health-care systems are designed to react on illness and optimized to manage illness. The widespread use of communication and information technologies facilitated the delivery of medical services at a distance, which is known as telemedicine [1]. Ranging from tele- and video-conferencing to robotic surgery, telemedicine extended the reach of medical services from elite medical institutions to remote villages in Finland and isolated Greek islands. New approach also forced changes in clinical practices, the most notable – introduction of the electronic medical record and information and communication technology. This new paradigm is known as eHealth [2],[3].

Recent developments in sensors, wearable computing, and ubiquitous communications have the potential of providing clinicians and users with tools and environments to gather physiological data over extended periods of time. This emerging concept is known as M-Health and represents the evolution of eHealth systems from traditional desktop telemedicine platforms to wireless and mobile configurations [4]-[6].

The main enabling technological trends for M-Health systems include:

- increased communication and computation capabilities of cell phones,
- the new generation of power efficient processors and communication controllers, and
- revolutionary changes in MEMS and nano sensor technologies enabling the embedded and implanted biomedical sensors and frequently used objects in our homes and offices

This chapter outlines enabling technologies and taxonomy of M-Health applications and introduces the ultimate concept in unobtrusive system organization for “anytime, anywhere” monitoring – wireless body area networks (WBAN) of intelligent wireless sensors. We discuss system integration and implementation issues, future trends, and possible applications.

22.2 OVERVIEW OF M-HEALTH SYSTEMS

22.2.1 Introduction

This section provides a brief overview of m-Health systems. In the following sections we divide those systems into two broad categories – Wireless Body Area Network (WBAN) based systems and systems based on smart clothes. However, as the section about smart clothes will discuss, these do not represent two completely disjoint sets of systems. We also present examples of wearable biomedical sensors to provide enough insight into different types of sensors and to serve as an illustration of our taxonomy.

Examples of M-Health systems and sensors are grouped according to the medical condition they apply or could apply to. We will discuss current and past commercial and research projects related to mobile monitoring of health conditions. Wireless telemetry has been available for a few decades, but wireless intelligent sensors capable of real-time signal processing have only been developed recently. Therefore, most of the work related to wireless intelligent sensors that will be discussed in this section represents research projects.

Cardiopulmonary monitoring

C1. *Medtronic* offers *Reveal® Plus Insertable Loop Recorder* [7][8], developed in collaboration with Division of Cardiology, University of Western Ontario. It provides up to 14 months of monitoring and data acquisition of critical cardiac events. Up to 40 minutes of history can be stored after an episode. This device weighs 17g, with the approximate volume of 8 mL. A previously recorded episode can be uploaded on demand to the computer for analysis.
C2. The implantable *EndoSure* MEMS blood pressure sensor from *CardioMEMS* [9],[10] was originally developed at Georgia Tech. It was the first implantable pressure sensor that combined wireless and microelectromechanical system (MEMS) technology to receive FDA clearance. The device is implanted during the aneurysm repair; at the same time that a graft is placed in the aneurysm sac,the sensor is inserted into the sac. It will take pressure readings inside the aneurysm sac; the readings can be transmitted from the sensor to an external device using Radio Frequency (RF) scavenging techniques.
C3. Scientists at the *d'Arbeloff Laboratory for Information Systems and Technology* at *MIT* have developed a *Ring Sensor* that continuously monitors heartbeat rate using a photoplethysmograph (PPG) signal and sends data wirelessly to a host computer [11]. The device has the shape of a ring and can be worn on a finger.
C4. Researchers at MIT and Massachusetts General Hospital have developed a behind-the-ear photo-plethysmogram-based sensor that uses a modified hydrostatic-based oscillometric method. It employs a MEMS accelerometer to reliably measure height [12]. Philips Research Europe develops an IEEE 802.15.4-based system that enables continuous cuffless blood pressure estimation using a waist ECG dry sensor and a behind-ear PPG sensor [13].
C5. Researchers at the University of Alabama in Huntsville developed a system for stress level assessment based on heart rate variability measurements [14]. The system performs synchronous measures of individual hearth rate during prolonged stressful training. Data are stored locally (for up to 60 hours) and collected wirelessly from the entire group of users using mobile gateways.

Diabetes control

D1. A typical example of a commercial system is *Symphony™ Diabetes Management System* [15] from *Sontra Medical Corporation*. Sontra offers a patch sensor that will continuously extract interstitial fluid, draw the analytes into the sensor, and measure and calculate the blood glucose concentration. The results are calculated and wirelessly sent to the receiver every 3.8 seconds. Currently, the system is only used for glucose measurements, but the company plans to add sensors to measure other analytes as well. DexCom [16] and Medtronic [17][18], among others, currently offer systems based on subcutaneous sensors that can be worn for up to 72 hours before replacement is needed. DexCom also has reported results for patients with surgically implanted long-term glucose level sensors.
D2. A "*skin breakdown detection*" device is intended for use by people suffering from diabetes [19]. The device is worn in the shoe, and records temperature, pressure, and humidity under the heel and metatarsal heads. The data are periodically evaluated off-line to detect abnormal conditions that may lead to skin breakdown; the goal is to prevent formation of foot ulcers which in a patient with advanced diabetes patient may lead to amputation.
D3. Medtronic MiniMed is an example of efforts to develop an artificial pancreas for diabetes patients. The first step in the development is an insulin pump (e.g. MiniMed Paradigm®) that disperses insulin based on the results of blood glucose measurements [18].
D4. LG Electronics and Healthpia [20] developed the *LG KP8400* cell phone that features a built-in glucose monitor. This cell phone is currently commercially available in some countries in Asia and is awaiting approval from the US Federal Drug Administration (FDA). The user places a drop of blood on a test strip and inserts the strip into a slot in cell phone. The glucose measurement is automatically sent to a caregiver.

Brain and muscle activity recording/stimulation

B1. Researchers from the *University of Washington*, *Caltech*, and *Case Western Reserve University* have developed a miniature implantable microcomputer [21], capable of recording nerve and muscle signals from small animals during their normal activity. They use flexible metallic needles to collect signals from nerve bundles and micromachined silicon probes to record activity of neural assemblies. However, to collect signals from individual neurons, scientists from the University of Washington are working on silicone MEMS probes that will mimic the performance of glass capillaries used on constrained animals. The implantable device consists of variable-gain amplifiers, a system-on-a-chip microcontroller, and a high-density memory. In this project, researchers decided to avoid antennas and charge pumps needed for RF-powered devices, due to size constraints of the implantable device. Instead, they plan to employ thin-film batteries.
B2. At the University of Michigan, *Center for Wireless Integrated Microsystems*, researchers developed a BiCMOS wireless stimulator chip [22], to be used in conjunction with micromachined passive stimulating microprobes. This design allows wireless and stand-alone operation for unlimited time, since the chip uses a 4MHz carrier signal to receive both data and power through inductive coupling. Total power dissipation of the chip is less than 10 mW and its surface area is about 13 mm^2.
B3. Another example of an RF-powered intelligent sensor is a miniature implantable wireless neural recording device [23][24] developed at the *University of California, Los Angeles*. This device records and transmits neural signals. The device size is less than 1 cm^2 and power dissipation has been measured at 13.8 mW. Tests have shown that the transmitting range is up to 0.5 m, and that demodulated signal is highly correlated with the original signals in the range between 5 mV and 1.5 mV.
B4. Medtronic has developed the *Activa Therapy* Deep Brain Stimulator, a surgically implanted device similar to a cardiac pacemaker, to block the brain signals associated with dystonia, Parkinson's disease and essential tremor. It delivers carefully controlled electrical stimulation to targeted areas within the brain. [25]

Gastrointestinal monitoring

G1. Researchers from the *Universities of Glasgow, Edinburgh and Strathclyde* are developing a capsule [26] traversing the gastrointestinal tract (part of *IDEAS* - Integrated Diagnostics for Environmental and Analytical Systems project). The capsule-based sensor gathers data that cannot be collected using traditional endoscopy. The device is battery powered and integrates sensors, processing, and RF bi-directional communication onto a single piece of silicon (current device size is 32×11.5mm) [27],[28].
G2. *Given Imaging* offers a commercially available capsule endoscopy system - *Given® Diagnostic System* [29],[30]. A disposable imaging capsule is swallowed by a patient and passes through the gastrointestinal tract while wirelessly transmitting images to a receiver worn on a belt. The images are received through an array of antennas; the antennas are used also to determine the exact location of the capsule.

Heterogeneous Sensor Systems

H1. The *U.S. Army Research Institute of Environmental Medicine* (USARIEM) and *The U.S. Army Medical Research and Materiel Command* (USAMMRC) led the project Warfighter Physiological Status Monitoring (WPSM) [31],[32]. The experimental system in development for that project includes sensors for heart rate, metabolic energy cost of walking, core and skin temperatures, geo-location, and activity/inactivity. Data collected by various sensors are transmitted wirelessly to a hub (worn on a soldier's belt) through a low-power PAN. Sensors are expected to be low-cost and disposable, capable of collecting data for up to a few weeks.

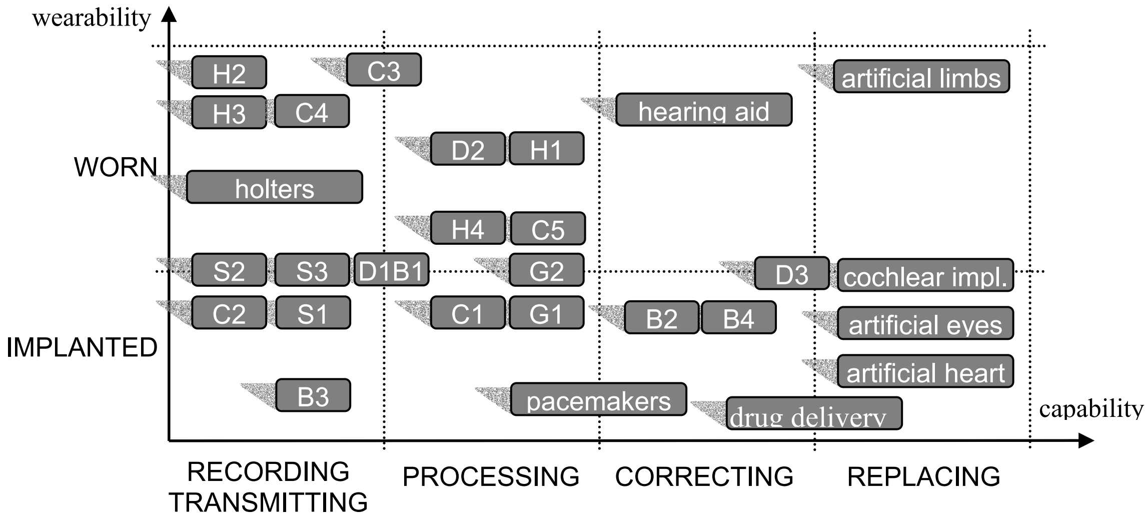

Figure 22.1 Taxonomy of usage (adapted from [33])

Aggregated data can be stored or forwarded to a warfighter's digital fighting system, command center, or in the future, to the Internet. The final system is expected to be able to predict the critical aspects of a soldier's performance under extreme conditions.

H2. The c*areTrends™ System*, offered by *Sensitron*, uses a combination of Bluetooth and IEEE 802.11b transmission to send patient vital signs data from a point-of-care to a server [34]. Currently, the company offers monitoring of blood pressure, pulse, temperature, weight, oxigen saturation, and respiration rate ; measurements are uploaded wirelessly to a Patient Communication Unit. The caregiver can use the hand-held unit to input pain scores, view and manage tests results and communicate with a careTrends access point.

H3. *Cleveland Medical Devices Inc*. markets *Crystal Monitor* [35] as a lightweight programmable wireless physiological monitor, capable of viewing and recording EEG, ECG, EMG, EOG, SpO_2, and other signals. Collected data is wirelessly transferred to a PC, up to 50 ft away, using the 2.4 GHz ISM band. The device can operate continuously for up to 12 hours on a set of 2 AA batteries. In addition, it uses a removable SD card to store over 60 hours of patient data for unattended monitoring.

H4. *Equivital Limited* developed the *Equivital™ system* for physiological life signs continuous monitoring and storage, to be used for military, emergency services, first responders, performance sports, and general healthcare. The system allows for real-time or off-line analysis of the data and incorporates the sensors for monitoring heart rate, respiratory rate, user's motion and position, temperature, and G shocks caused by falls and heavy impacts. It also provides a rudimentary cognitive response from the user to asses his consciousness and awareness [36].

H5. The 3G wireless cellular data system can be used for direct transmission of all patient data (video, medical images, ECG signals, etc.) [37].

22.2.2 Taxonomy of M-Health Systems

We introduce two taxonomy groups. One classifies personal medical devices based upon their *usage*, while the other one deals with their *implementation*. The taxonomies allow us to abstract from a particular application and devise design principles that hold for all applications that fall within a given category. Our taxonomy groups will include some devices not covered in the examples listed in the previous section. The functionality of these devices is either well known, or goes beyond the scope of this paper – defibrillators/pacemakers, hearing aid devices, artificial heart, artificial limbs, artificial eyes, drug pumps, etc. We include them in the taxonomy for completeness, and to show possible areas for future medical applications of wearable computing.

Description of taxonomy of usage

Our taxonomy of usage for personal medical devices is shown in Figure 22.1. The taxonomy places devices in a 2-D space defined by two axes: *capability* and *mode of wearability*. A third axis could also be introduced, to address duration of the required service. We see four broad categories along the capability axis: *recording/transmitting, processing, correcting*, and *replacing*. We define these functions as follows:

- *Recording/transmitting:* Devices that store or send relevant signals and data from the patient, but do not evaluate the signals (except for signal conditioning) in any manner or provide feedback to the patient. The signals are evaluated off-line.
- *Processing:* Devices that process relevant signals and *provide immediate feedback* to the patient about his or her current condition. This feedback may or may not be continuous, as in the case of an ECG monitor that provides alerts of impending cardiac events. These processing devices may also store the signals so that they may be further processed off-line, just like the recording devices.
- *Correcting:* Devices that provide appropriate stimuli directly to a malfunctioning organ in order to correct its behavior.
- *Replacing:* Devices that replace an organ entirely (prostheses).

There may be another category in the future, somewhat related to the correcting category, but going a step further: Devices that train the body in some way but then can be removed, analogous to braces for the teeth. For the purpose of this taxonomy, we treat as implanted all the devices that are inside the user's body, even if they were not inserted surgically (i.e. even if they were swallowed, inserted subcutaneously by the user, etc.). In the not-too-distant future, devices may be small enough to be introduced into the body by other means, such as inhalation. Some devices straddle the borders between categories. For more information, the reader should see [33].

Description of taxonomy of implementations

The taxonomy of implementations classifies systems according to the system mobility (represented in Figure 22.2). It characterizes systems along two axes: *patient mobility* and *gateway availability*. We use this taxonomy to emphasize the fact that the development of medical monitoring equipment constantly goes in the direction of increased patient mobility and the flexibility of positioning of external monitoring equipment. In the past, patient monitoring has been performed in hospital or in the lab with patient strapped to the fixed monitoring system and not able to move about freely. With technological advances wearable monitors allowed patient to walk around the hospital. The ultimate goal would be normal patient mobility where the patients are monitored as they go about their everyday routine with the miniaturized monitoring equipment concealed on the person.

In most modern systems, data are not only provided to the user, but at the same time forwarded to a hospital information or telemedical system. Therefore, it is necessary to have access points (or gateways) to medical networks. One of the main system design issues is availability of these gateways, which, depending on the application, can be implemented as network of fixed gateways within a medical institution, health-kiosks throughout the city, or global access point in the case of satellite based systems. The smaller the size of the monitoring device, the more limited will be the available power for signal transmission. One design solution is to keep communication distance short, but to allow access point to move around and connect with individual monitors. Alternatively a limited set of access points are available to monitoring devices that move in and

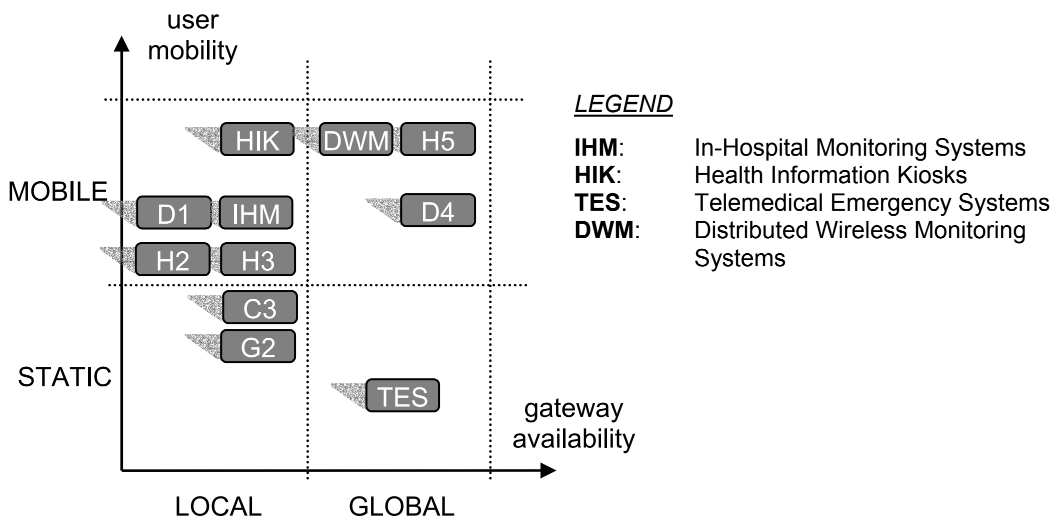

Figure 22.2 Taxonomy of implementations (adapted from [33])

out of reach of the access points. Such solutions keep the power consumption of a monitor low, at the cost of delayed data delivery.

We define two broad categories along each of the axes *patient mobility* and *gateway availability* – the patient can be either *mobile* or *static*, while the gateway availability can be either *local* or *global*. A moving gateway or a group of local gateways will be treated as a global gateway. The ultimate goal of ubiquitous personal health monitoring systems is maximal user mobility.

Using these axes, we divide systems into four categories and provide some typical examples:

- Local Gateway / Static Patient (**LGSP**) is typical of older monitoring systems, such as fixed bed-side hospital monitors.
- Local Gateway / Mobile Patient (**LGMP**). This type of system is usually used in wireless in-hospital or home monitoring systems and allows patient mobility within the range of the network of access points. Another possible future application of LGMP is *health information kiosks* that could be used to collect data from personal monitors on different locations in town.
- Global Gateway / Static Patient (**GGSP**). A typical example would is an emergency response vehicle globally connected with a medical network, while patients are incapacitated.
- Global Gateway / Mobile Patient (**GGMP**) allows patients to move freely over large areas, which is made possible by distributed wireless monitoring systems. Those systems either employ cellular-phone infrastructure or mobile gateways as access points.

22.2.3 Smart Clothes

Smart clothes are extensions to networks of independent wireless medical sensors. Smart clothes are not yet widely employed, but once current problems with fabrication and usability are solved and their costs come down, wider acceptance is expected. Smart clothes were first applied for monitoring of patients, athletes, and high risk workers, but applications for everyday life followed very soon afterwards [38].

Smart clothes can be used to detect *biomechanical* (e.g. respiratory or activity related body movement, posture monitoring, etc.), *bioelectrical* (ECG, EMG, EEG, etc.), and other parameters such as temperature. The IEEE EMBS technical committee for Wearable Biomedical Sensors and Systems [39] considers smart clothes as the core of a wearable biomedical system, because are convenient, personal, and close proximity of the source of most biomedical signals. In addition, they can be worn withlittle chance of disclosing a possible medical conditions of its users.

In their simplest form, smart clothes only provide the interconnectivity between sensors, electrodes, and external electronics. However, if smart clothes are to become truly wearable m-Health systems, electronics need to be embedded into clothing as well. Ideally an entire smart clothes system should wirelessly communicate with electronic devices that its users would normally use. For example, a smart phone can be used to display the current state of the smart clothes system, issue warnings, and relay information to higher tiers of a medical system.

Several major challenges need to be addressed successfully before smart clothes will be widely employed:

- *Wearability*. Many of the characteristics that define wearability (unobtrusiveness, stretchability, washability, etc) are in direct conflict with the requirements for the increased functionality of smart clothes (more sensors embedded in clothing, integrated processing and display, etc.)
- *Interconnectivity*. Sensors, electrodes and conductive yarns are sometimes built in different technologies. This can create difficulties in interfacing them electrically, and can also compromise the flexibility of the yarn because of differences in mechanical properties.
- *Motion and other artefact suppression*. Signal integrity is crucial in any medical system, and becomes even more important in the case of wearable systems. Smart clothes, by their very nature, are prone to different types of artefacts (interference of other personal electronic devices, difficulties with propagation of signals near and through the human body, etc.) among which the motion artefacts are especially prominent. Motion and other artefacts can be reduced or completely removed through careful design of sensors and interconnections, sensor redundancy, signal conditioning, and signal processing. However, requirements for increased signal integrity are often conflicting with requirements related to acceptable levels of comfort while wearing smart clothes.

A number of commercially available products are available – Sensatex *SmartShirt System* [40],[41], VivoMetrics *LifeShirt System* [42], Information Society Technologies *Wealthy* [43], etc. The universities are also performing a range of research activities in the same area [44]-[48].

22.3 M-HEALTH BASED ON WIRELESS BODY AREA NETWORKS (WBAN)

22.3.1 WBANs: General Concepts

Recent technological advances in sensors, integrated circuits, and wireless networking facilitate wireless sensor networks that are deeply embedded in their native environments. Wireless sensor networks are highly suitable for many applications, such as habitat monitoring [49], machine health monitoring and guidance, traffic pattern monitoring and navigation, plant monitoring in agriculture [50], and infrastructure monitoring. The current technological and economic trends will enable new generations of wireless sensor networks with more compact and lighter sensor nodes, with more processing power and more storage capacity. In addition, the ongoing proliferation of wireless sensor networks across many application domains will result in a significant cost reduction.

One of the most promising application domains is health monitoring [51], and within healthcare Wireless body area networks (WBAN) in particular are emerging as promising enabling technologies to implement m-Health. A WBAN for health monitoring consists of multiple sensor nodes that can measure and report the user's physiological state. A WBAN for health monitoring may also feature active devices for control of the user's physiological state – for example, some WBAN nodes may be responsible for drug delivery. These sensor nodes are strategically placed on the human body. The exact location and attachment of the sensor nodes on the human body depends on the sensor type, size, and weight. Sensors can be worn as stand-alone devices or can be built in jewelry, applied as tiny patches on the skin, hidden in the user's clothes or shoes, or even implanted in the user's body. Each node in the WBAN is typically capable of sensing, sampling, processing, and wirelessly communicating one or more physiological signals. The exact number and type of physiological signals to be measured, processed, and reported depends on end-user application and may include a subset of the following physiological sensors:

- an electrocardiogram (ECG or EKG) sensor for monitoring heart activity
- an electromyography (EMG) sensor for monitoring muscle activity
- an electroencephalography (EEG) sensor for monitoring brain electrical activity
- a photoplethysmography (PPG) sensor for monitoring of pulse and blood oxygen saturation
- a cuff-based pressure sensor for monitoring blood pressure
- a resistive or piezoelectric chest belt sensor for monitoring respiration
- a galvanic skin response (GSR) sensor for monitoring a subject's autonomous nervous system arousal
- a blood glucose level sensor
- a thermistor for monitoring of body temperature.

In addition to these sensors, a WBAN for health monitoring may include sensors that can help determine user's location, discriminate between user's states (e.g., laying, sitting, walking, running), or sensors that can help estimate the type and level of the user's physical activity. These sensors typically include the following:

- a localization sensor (e.g., Global Positioning System – GPS)
- a tilt sensor for monitoring of trunk position
- a gyroscope-based sensor for gait-phase detection
- accelerometer-based motion sensors on extremities to estimate type and level of the user's activity
- a 'smart sock' or an insole sensor to count steps and/or delineate phases and distribution of forces during individual steps.

Environmental conditions may often influence the user's physiological state (e.g., it has been shown that blood pressure may depend on the subject's ambient temperature) or accuracy of the sensors (e.g., background light may influence the readings from photoplethysmography sensors). Consequently, WBANs may benefit from integrating the third group of sensors that provide information about environmental conditions, such as:

- humidity
- light
- ambient temperature
- atmospheric pressure
- noise.

All technological trends and the ability to measure a wide variety of physiologically important signals indicate that WBANs are well positioned to become a key component in providing continual, unobtrusive, and affordable monitoring in healthcare.

22.3.2 System Architecture and Organization

Typically, a WBAN will form the lowest tier (Tier 1) of a multi-tier medical information system for health monitoring. Figure 22.3 illustrates a general system architecture of a medical monitoring information system which includes a Personal Server at tier 2 and a series of medical servers at tier 3. The exact system architecture and the number of system tiers depend predominantly on target applications, available infrastructure, and type and the number of users. Though we focus on the health monitoring system described in Figure 22.3 , we will identify possible alternatives to this type of system organization.

The WBAN in Figure 22.3 includes one heart sensor and two motion sensors, one attached at a wrist and the other one to an ankle. One possible target application for such a WBAN is for fitness monitoring – helping track duration, type, and intensity of regular daily exercises. A similar system can be used for monitoring of cardiac patients during a rehabilitation period at home. The heart sensor can operate in multiple modes reporting either (i) a raw ECG signal (from one or multiple channels), (ii) time-stamped heart beats, or (iii) averaged heart rate over a certain period of time. The motion sensors, each equipped by a 3-D accelerometer, can also operate in several modes reporting either (i) a raw acceleration signals for X, Y, and Z axes, (ii) extracted features (e.g., time-stamped steps or phases of a step), or (iii) an estimated level of activity (e.g., AEE – activity induced energy expenditure over a certain period of time). The WBAN sensor nodes together with a WBAN network coordinator, attached to the Personal Server, compose a wireless body area network. Upon configuration the WBAN continually performs sensing, sampling, and signal processing. Sensors are waiting for command and control messages from the WBAN coordinator and report continual sensor readings or events of interest as they occur.

Tier 2 encompasses the Personal Server (PS) application. The PS is responsible for a number of tasks, providing a transparent interface to the wireless sensor nodes, an interface to the user, and an interface to the medical server. The interface to the WBAN includes network configuration and management. The network configuration encompasses the following tasks: sensor node registration (type and number of sensors), initialization (e.g., specify sampling frequency and mode of operation), customization (e.g., run user-specific calibration or user-specific signal processing procedure upload), and setup of a secure communication (security key exchange). Once the WBAN network is configured, the PS application manages the network and takes care of channel sharing, time synchronization, data retrieval and processing, and fusion of the data. Based on synergy of information from multiple physiological, location, activity, and environmental sensors; the PS application can determine the user's state and his or her health status; in addition, the PS can provide feedback through a user-friendly and intuitive graphical or audio user interface. Finally, if a communication channel to the medical server is available, the PS can establish a secure link to the medical server and send condensed or detailed reports about the user's health status. These reports can be processed, displayed, and integrated into the user's medical record. However, if a link between the PS and the medical server is not available, the PS should be able to store the data locally and initiate data uploads when a link becomes available. Depending on the use scenario, the PS application can run on a smart phone (as illustrated in Figure 22.3), or a Wireless Wide Area Network (WWAN)-enabled Personal Digital Assistant (PDA), or on a home personal computer.

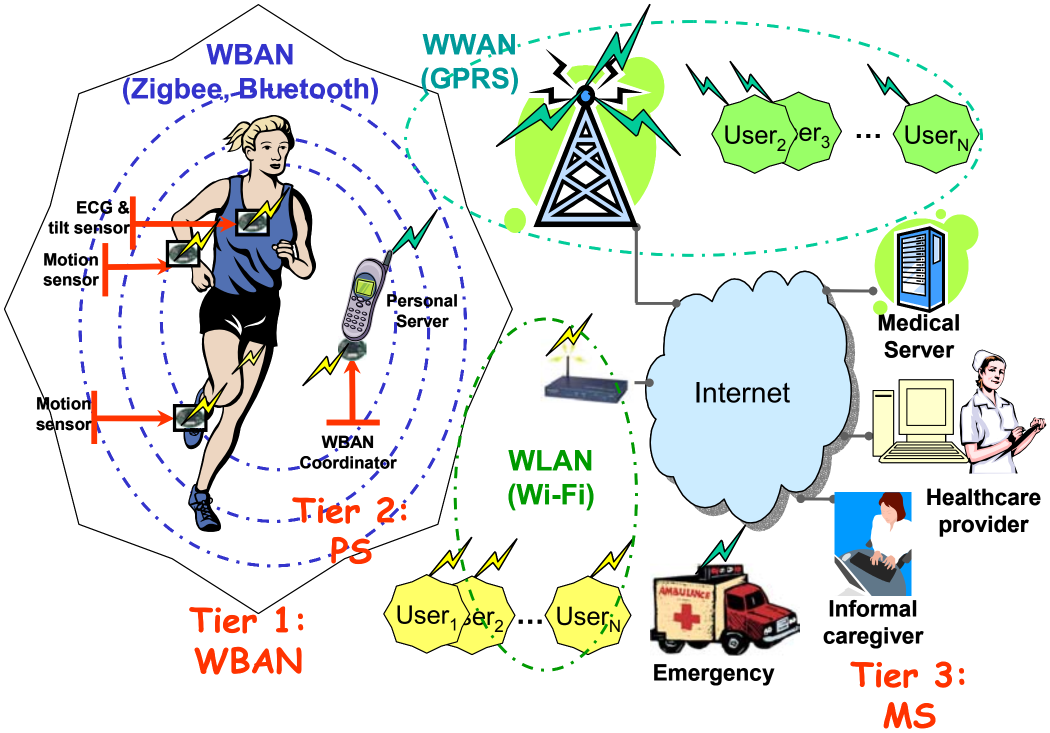

Figure 22.3 A multi-tiered health monitoring system based on WBAN.

Tier 3 includes a medical server accessed via the Internet. In addition to the medical server, the last tier may encompass other servers, such as informal caregivers, commercial health care providers, and even emergency services. The medical server keeps electronic medical records of registered users and provides various services to the users, medical personnel, and informal caregivers. It is the responsibility of the medical server to authenticate users, accept health monitoring session uploads, format and insert the session data into corresponding medical records, analyze the data patterns, recognize serious health anomalies in order to contact emergency care givers, and forward new instructions to the users, such as physician prescribed exercises. The patient's physician can access the data from his/her office via the Internet and examine it to ensure the patient is within expected health metrics (heart rate, blood pressure, activity), ensure that the patient is responding to a given treatment or that a patient has been performing prescribed exercises. A server agent may inspect the uploaded data and create an alert in the case of a potential medical condition.

The large amount of data collected through these services can also be utilized for knowledge discovery through data mining. Integration of the collected data into research databases and quantitative analysis of conditions and patterns likely will prove invaluable to researchers trying to link symptoms and diagnoses with historical changes in health status, physiological data, or other parameters (e.g., gender, age, weight). In a similar way a WBAN-PS-medical server infrastructure could significantly contribute to monitoring and studying of drug therapy effects.

22.3.3 WBAN Applications

WBANs can be used in a number of applications, from fitness/exercise monitoring of healthy users, to monitoring of patients with chronic or impeding medical conditions in hospitals and ambulatory settings, or early detection of disease, or emergency care. The table below lists medical conditions and corresponding physiological signals relevant for given condition.

Table 1. Medical conditions and suggested minimal WBAN configurations.

Medical Condition	WBAN sensors
Cardiac Arrhythmias/Heart Failure	Heart rate/ECG, blood pressure, activity
Asthma	Respiration rate, peak flow, oxygen saturation
Cardiac Rehabilitation	Heart rate/ECG, activity, environmental sensors
Post-operative Rehabilitation	Heart rate/ECG, temperature, activity
Diabetes	Blood glucose level, activity, temperature
Obesity/Weight loss programs	Heart rate, smart scale, activity (accelerometers)
Epilepsy	EEG, gait (gyroscope, accelerometers)
Parkinson's Disease	Gait, tremor, activity (gyroscope, accelerometers)

For each medical condition, a series of WBAN solutions can be devised; it is not the intention to cover a broad series of medical conditions. Instead, we opt to present a hypothetical case study of a representative condition, in our example a patient recovering from a heart attack, to illustrate the usefulness of WBAN-based health monitoring systems. We discuss many common problems patients face after a heart attack and describe how our system can be used to address these problems; in addition we will show how WBANs will provide advantages over typical present day solutions.

Case Example: Peter Petrovich is recovering from a heart attack. After the release from the hospital he attended supervised cardiac rehabilitation for several weeks. His recovery process goes well, and Peter is to continue a prescribed exercise regimen at home. However, the unsupervised rehabilitation at home does not go well for Peter. He does not follow the exercise regimen as prescribed. He exercises, but does not truthfully disclose to the treating healthcare providers the minimal intensity and duration of his exercise. As a result, Peter's recovery is slower than expected which raises concerns about his health status within his healthcare providers: is the damage to Peter's heart greater than initially suspected, or does he not follow medical advice? The latter question is no longer verifiable as his physician has no quantitative way to verify his adherence to the exercise program.

A WBAN-based health monitoring system offers a solution for Peter and all persons undergoing cardiac rehabilitation at home as well as the healthcare providers. Peter is equipped with a WBAN-based ambulatory health monitoring system. Tiny electronic inertial sensors measure movement on extremities and the number of steps Peter makes, while electrodes on the chest can measure Peter's heart activity. The WBAN provides continual reporting of heart rate and activity induced energy expenditure. The time and duration of his normal and exercise activity are recorded, and the level of intensity of the exercise can be determined by calculating an estimate of energy expenditure from the motion sensors. The information is available on Peter's smart phone that acts as his Personal Server. The Personal Server may also assist Peter in his exercise efforts: it may alert him that he has not initiated or is not reaching his intended goals, or generate warnings in case of excess exercise (e.g., heart rate is above the maximum threshold for a person of his age, weight, and condition).

Through the internet or cell phone-connected server, his healthcare providers can collect and review all data, verify that Peter is exercising regularly, issue new prescribed exercises, adjust data threshold values, and schedule office visits. Peter's description of his progress continues to be important but his healthcare providers no longer need to rely on only subjective descriptions, but instead have an objective and quantitative data set of his level and duration of exercise. In addition, Peter's parameters of heart rate variability provide a direct measure of his physiological response to the exercise serving as an in-home stress test. Substituting these remote stress tests and data collection for in-office tests, Peter's healthcare providers reduce the number of office visits. This decreases healthcare costs and makes better use of the healthcare providers' time. In urgent cases, however, the Personal Server can directly contact Emergency Medical Services (EMS) if the user subscribes to this service. Figure 22.4 illustrates one possible data flow.

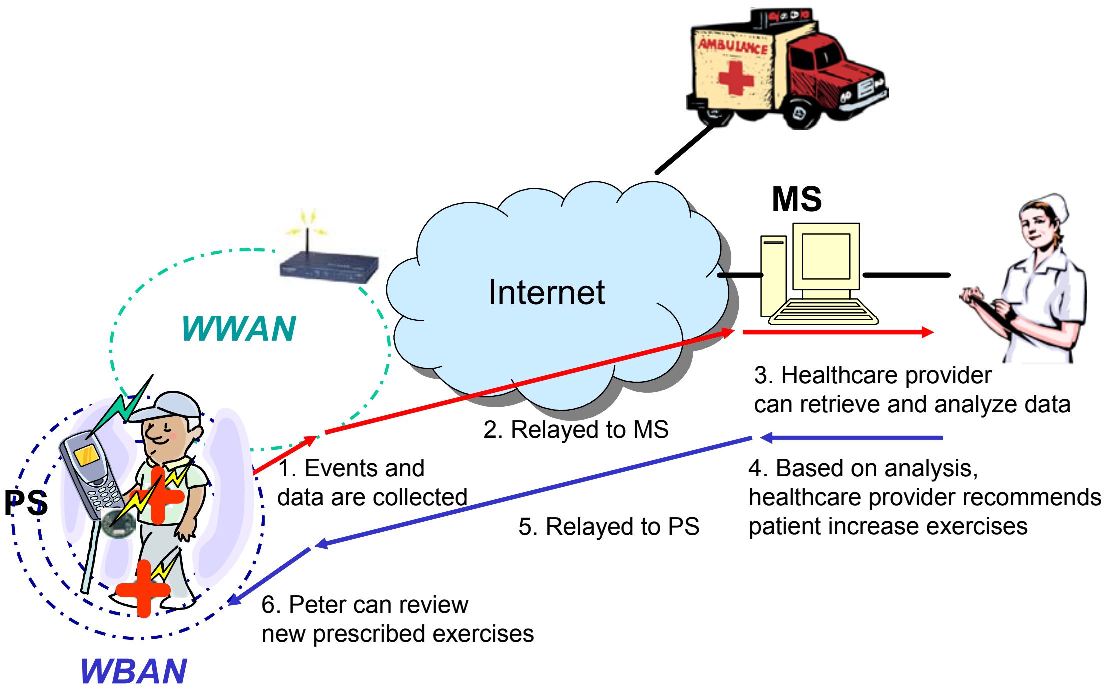

Figure 22.4 Example of data flow in the proposed WBAN healthcare monitoring system.

22.4 WIRELESS INTELLIGENT SENSORS FOR M-HEALTH

Each WBAN sensor node typically performs four basic tasks, as follows:

1. Sensing and sampling of relevant physiological or environmental signals,
2. Digital signal processing of input signals (e.g., filtering, feature extraction, data compression, etc),
3. On-sensor data buffering, and
4. Wireless communication with the Personal Server.

Consequently, a WBAN node encompasses the following physical resources (i) sensor devices (ii) signal conditioning circuitry, (iii) analog-to-digital converter circuitry, (iv) processing units, (v) memory, (vi) communication I/O devices (e.g., radio interfaces), and power supply (Figure 22.5). In addition to the monitoring function, a sensor node may include actuators, capable of changing or reacting to the user's state. For instance, a WBAN sensor node may include a drug delivery pump that is automatically activated once certain conditions are met; a blood glucose sensor may be augmented with actuators that control dosage of insulin. Another example of an acting sensor node is an EEG sensor augmented with actuators for electrical neural stimulation to prevent the development of epileptic seizures.

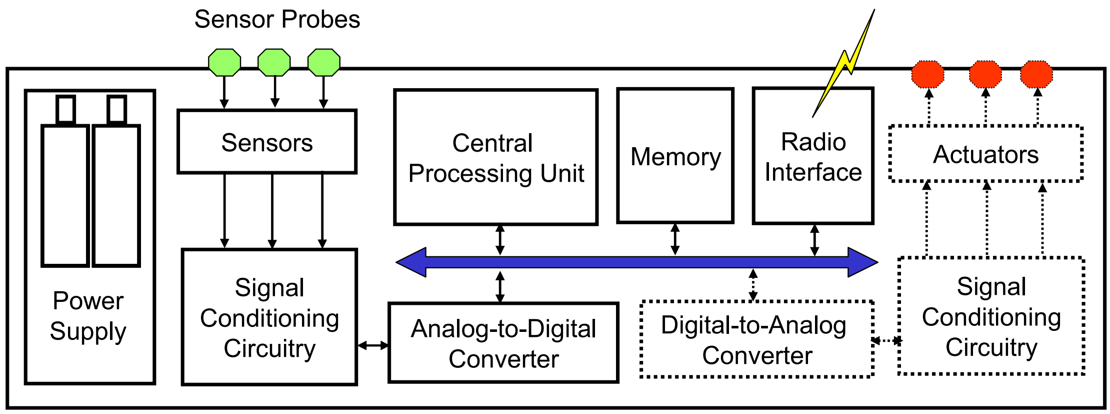

Figure 22.5 WBAN node architecture.

The actual hardware organization of each sensor node is greatly influenced by main design requirements for the WBAN, such as: functionality, wearability, ease of deployment, durability and reliability, security, and interoperability.

Functionality. The end user application determines (i) the number and type of vital statistics the WBAN needs to provide, (ii) the required precision and accuracy of sensor readings, and (iii) the sample frequency and frequency of reported data. For example, a fitness monitoring application targeting healthy users may not require an electrocardiogram and may also tolerate possible loss of heart beat messages. However, arrhythmia monitoring applications require a very precise heart beat stream or even raw electrocardiogram; possible loss of heart beat events is unacceptable as it may result in false alarms or missed events.

Wearability. To achieve non-invasive and unobtrusive continuous health monitoring, WBAN sensors should be lightweight and have a small form factor, so they can be built into clothes or applied as tiny patches on the skin. The size and weight of current sensor platforms are predominantly determined by the size and weight of batteries. However, a battery's capacity is directly proportional to its size. It is desirable to provide an extended period of operation without the need for battery replacements because multiple sensors requiring frequent battery changes will hamper users' acceptance of wearable systems. In addition, longer battery life will decrease WBAN operational costs. Consequently, energy efficiency is one of the key design requirements for WBAN sensor nodes as it improves both wearability and user's compliance. Electrophysiological signals rely on contact electrodes with gels used to reduce contact resistance. It is known that prolonged wear of resistive electrodes can result in skin irritation. A number of other problems can also arise. For example, if the contact gel dries out, the signal quality likely deteriorates. Worse, the electrode pulls away from the skin completely. This problem can be overcome by using recently introduced insulated non-contact bio-electrodes [52].

Deployment and durability. The ideal location of specific WBAN sensors is still an open issue – for instance, for activity research the research community is investigating a minimal set of motion sensors and their placement that will enable almost perfect discrimination of the user's states. Sensor attachment is also a critical factor, since the movement of loosely attached sensors creates spurious oscillations after an abrupt movement; such signal artefacts can generate false events or mask real events. The sensor nodes also need to be robust and durable, so that environmental conditions and time will not influence sensor readings.

Reliable communication. Reliable communication is of utmost importance for medical applications that rely on WBANs. The communication requirements of different medical sensors vary with required sampling rates, from less than 1 Hz to 1000 Hz. One approach to improve reliability is to move beyond telemetry by performing on-sensor signal processing. For example, instead of transferring raw data from an ECG sensor, one can perform feature extraction on the sensor, and transfer only information about an event (e.g., QRS features and the corresponding time stamp of the R-peak). In addition to reducing heavy demands for the communication channel, the reduced communication requirements decrease total energy consumption, and consequently increase battery life. A careful trade-off between communication and computation is crucial for optimal system design.

Security. Another important issue is overall system security. The problem of security arises at all three tiers of a WBAN-based telemedical system. At the lowest level, wireless medical sensors must meet privacy requirements mandated by the law for all medical devices and must guarantee data integrity. Though security key establishment, authentication, and data integrity are challenging tasks in resource constrained medical sensors, the relatively small number of nodes in a typical WBAN and short communication ranges make these requirements achievable. [53]

Interoperability. Wireless medical sensors should allow users to easily assemble a robust WBAN depending on the user's state of health. Standards that specify interoperability of wireless medical sensors will promote vendor competition and eventually result in more affordable systems.

22.4.2 Sensor Architecture

Physical sensors are devices that detect and convert natural physical quantities into analog signals (voltages and currents). Electrophysiological signals, such as ECG, EEG, EMG, and GSR are sensed directly through contact or contactless electrodes attached to certain parts of the human body. Others parameters (physical quantities), such as blood pressure, blood glucose level and body motion are converted into electrical signals using corresponding transducers. For example, MEMS-based accelerometers attached to the human body convert acceleration measured on that location into an electrical signal. Often these electrical signals need to be conditioned before sampling. Signal conditioning circuits amplify signals that are too weak (e.g., ECG signals are in millivolts and these signals are typically amplified into the range of Volts before sampling). Other signal conditioning circuits may reduce the signal level or reduce the frequency range of the signal through filtering. Finally, analog signals are converted into corresponding digital code that can be further processed. These three functions, sensing (with transducing), signal conditioning, and analog-digital (AD) conversion, are typically implemented by multiple integrated circuits, but current trends are toward integration of all these functions into a single-chip solution.

The WBAN physical sensors must satisfy a key requirement: unobtrusive and easily deployable. They also need to have a stable function over long- time periods and be easy to calibrate. Sensor characteristics, such as, accuracy, resolution, sampling rate, and the number of channels depend on health monitoring application.

Table 2 shows for a series of typical WBAN sensors min-max sampling rate, min-max resolution, number of channels, type of sensor probes, and preferred sensor location.

Table 2. Physiological signals: sampling rates, precision typical for wearable health monitoring applications, and likely location of deployment.

Physiological	**Sampling rate [Hz]**	**Precision [bits]**	**Channels**		
parameter	*(min – max)*	*(min – max)*	*(min– max)*	*Type of sensing device*	*Placement*
ECG (per channel)	(100 – 1000)	(12 – 24)	(1 – 3)	Electrodes	Chest
EMG	(125 – 1000)	(12 – 24)	(1 – 8)	Electrodes	Muscles
EEG	(125 – 1000)	(12 – 24)	(1 – 8)	Electrodes	Head
PPG	(100 – 1000)	(12 – 16)	1	Photodiode	Ear or finger

Blood Pressure	(100 – 1000)	(12 – 24)	1	Pressure cuff	Arm or finger
Respiration	(25 – 100)	(8 – 16)	1	Elastic chest belt or electrodes	Chest
Blood Glucose	< 0.01	(8 – 16)	1	Chemical	Skin
GSR	(50 – 250)	(8 – 16)	1	Electrodes	Fingers
Skin Temperature	< 1 in 60 sec	(16 – 24)	1	Thermistor probe	Wrist/Arm
Localization	(0.01 – 10)	(80 – 120)	1	GPS receiver	Personal Server
Gait	(25 – 100)	(16 – 32)	(1 – 3)	Inertial Gyroscope	Chest
Activity	(25 – 100)	(12 – 24)	3	Accelerometers	Chest, Extremities
Steps	(2 - 100)	(1 – 16)	(1 – 8)	Mechanical foot switch	Shoe insole
Humidity	< 1 in 60 sec	(12 – 16)	1	--	Attached to PS
Light	< 1 in 60 sec	(12 – 16)	1	--	Attached to PS
Ambient temperature	< 1 in 60 sec	(12 – 16)	1	--	Attached to PS
Atmospheric Pressure	< 1 in 60 sec	(12 – 16)	1	--	Attached to PS
Ambient Noise	< 1 in 60 sec	(12 – 24)	1		Attached to PS

Computing

Processing resources on a WBAN node include one ore more processors/microcontrollers. They are responsible to coordinate sampling activities; pre-process sampled data (e.g., filtering); perform feature extraction; manage local memory resources; and initialize, control, and manage WBAN communication. In order to meet strict requirements for small size and weight, the WBAN sensor nodes have limited processing and storage resources. Processing and storage requirements of a WBAN node vary greatly depending on physiological signals (type, resolution, sampling rate) and WBAN application requirements. For example, a WBAN node equipped with one or more foot switches poses minimal requirements for processing power. Similarly, transmission of a raw ECG signal does not require significant processing power; however, a heart sensor featuring morphological ECG analysis requires higher processing power.

WBAN nodes must have enough storage resources for temporary data buffers to accommodate for lost messages and intermittent communication. The size of these buffers is determined by allowed event latency and available memory capacity. Event latency requirements define the maximum propagation delay from the moment an event has been detected on a WBAN node till the moment the Personal Server application has received that event. For example, a WBAN node or multiple nodes monitoring posture of an elderly person must notify the Personal Server that a fall has been detected within a couple of seconds, so that the Personal Server may create and alert event for emergency services or home health care providers. Contrary to this, a WBAN application targeting monitoring of physical activity and exercise of a healthy user does not pose strict requirements for event delay propagation. The data upload does not need to be in real-time and it can be done once a day. However, even in this case, available memory capacity imposes the limitation on the total operating time if we do not want to lose any data (see Example #3).

Wireless Communication

The radio interface of a WBAN node must be able to receive command and calibration messages from the network coordinator and to transmit sensor readings, extracted events, and status messages to the network coordinator. Emerging wireless standards and the expected proliferation of large-scale wireless sensor networks enable continual advances in radio interfaces – each new generation of radio devices provides higher bit rates at lower cost and energy consumption with higher levels of integration and miniaturization.

System designers need to estimate the required application bandwidth. In general, bandwidth depends on the number and type of sensor signals, their sampling frequency, and sample sizes. The required communication bandwidth may be estimated as follows:

$$SBW = \sum_{i=1}^{N} \sum_{j=1}^{Nch_i} Fs_i \cdot SS_i \cdot Rov_i \text{, where,}$$

SBW – represents the total required system bandwidth (without communication protocol overhead)

N is the total number of monitored signals in the system (BAN)

Nch_i is the number of channels of the signal *i*

FS_i is sampling frequency of the signal *i*

SS_i is a sample size of the signal *i*.

The WBAN communication may feature a custom wireless protocol or a wireless personal area network based on IEEE 802.15.4 (Zigbee) or IEEE 802.15.1 (Bluetooth) standards. ZigBee is developed for control and home automation applications and has a low data rate, low power consumption and short latency, and supports short packet devices and a large number of devices in the network. Bluetooth on the other hand uses a higher data rate, higher power consumption, and works with large packet devices.

Table 3 shows the main characteristics of Zigbee and Bluetooth.

Table 3. Zigbee vs. Bluetooth: Comparison of main characteristics

Parameter	**Zigbee**	**Bluetooth**
Frequency band	2.4 GHz	2.4 GHz
Modulation technique	Direct Sequence Spread Spectrum (DSSS)	Frequency Hopping Spread Spectrum (FHSS)
Protocol stack size	4- 32 KB	250 KB
Battery changes	Rare	Intended for frequent recharges
Max bandwidth	250 Kb/s	750 Kb/s
Max range	up to 70 meters	1 – 100 meters
Typical network join time	30 ms	3 sec
Network size	65536	8

Putting everything together: Actis System

In the spirit of the system architecture described above, a prototype WBAN for health monitoring has been developed [54],[55]. Figure 3 shows a photograph of the prototype components. The prototype includes two activity sensors (ActiS), an integrated ECG and tilt sensor (eActiS), and a Personal Server. Each sensor node includes a custom application specific board and uses the Tmote sky platform for processing and 802.15.4 compliant wireless communication [56],[57]. The Personal Server runs either on a laptop computer or a WLAN/WWAN-enabled handheld PocketPC. The network coordinator with wireless ZigBee interface is implemented on another Tmote sky module that connects to the Personal Server through a USB interface. For an alternative setting, a custom network coordinator has been developed featuring a ZigBee wireless interface, an ARM processor, and a compact flash interface to the Personal Server (Figure 22.6). More details about prototype architecture, implementation issues, communication protocol, and software architecture can be found in [54],[55].

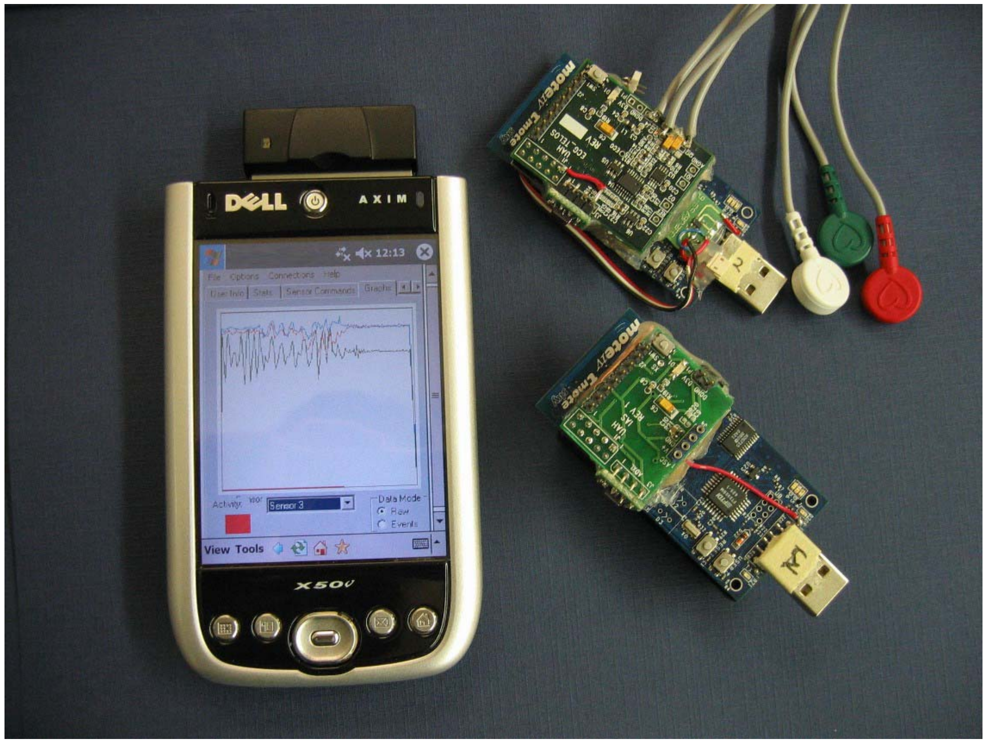

Figure 22.6 Prototype WBAN. From left to right: the Personal Server with Network Coordinator, ECG sensor with electrodes, and a motion sensor.

Examples

Example #1: Calculate the min-max bandwidth requirements [B/sec] of a heart sensor that streams a subject's 3-channel ECG signal.
Solution: Bandwidth = [Sampling rate] * [Number of bits per sample] * [Number of channels] = [100, 1000] * 2 * 3 = [600 B/sec, 6000 B/sec]

Example #2: Calculate min-max bandwidth requirements of a heart sensor that streams RR-intervals.
Solution: Normal heart rate is in the range of 30 bpm to 240 bpm. The heart sensor detects each heart bit and time-stamp it. Therefore, an R-peak event is represented by an associated time-stamp. If we assume a common time tick of (1/32 kHz) = 31.25 ms, the first step is to determine the number of bits needed for each time-stamp. For the maximum heart rate of 240 bpm, the number of clock ticks is (60/240)*32,000 = 8000. For minimum heart rate of 30 bpm, the number of clock ticks is (60/30)*32,000 = 64,000. To represent this range (8000 – 64,000), a 2 byte unsigned integer will suffice. Consequently, the required min-max bandwidth is in the range of (30 bpm *2 B)/60 = 1 Byte/sec, and (240 bpm *2 B)/60 = 8 B/sec.

Example #3: Consider a WBAN node with a 3-level memory hierarchy, including a) on-chip local RAM memory, b) on-chip or on-board flash memory, and c) external flash disk. Assume that available memory capacity for data buffering are as follows:

M_1 – RAM memory capacity – 5KB (40Kb)
M_2 – flash memory capacity 4Mb
M_3 – flash disk capacity 1GB (8 Gb)

What are expected operating times for an ECG sensor node transmitting (a) a single channel ECG signal (sampling rate = [100, 1000], resolution = 16 bits) and (b) RR-intervals for each level of the memory hierarchy?

Solution: The system operating time can be determined as follows:

$$OT = M_i / BW_i$$

where Mi is the given memory capacity, and BWi is the amount of data to be stored in memory (sampling_rate * sample_length).

(a)

OT_1 (RAM) = M_1 / BW_{ECG} = 40 Kb / [1,600 .. 16,000] bps = [2.56 .. 25.6] s
OT_2 (flash_memory) = M_2 / BW_{ECG} = 4Mb / [1,600 .. 16,000] bps ≈ [0.72 .. 7.2] hours
OT_3 (flash_disk) = M_3 / BW_{ECG} = 8Gb / [1,600 .. 16,000] bps ≈ [2.5 .. 25] days

(b)

OT_1 (RAM) = M_1 / BW_{RR} = 40 Kb / [8 .. 64] bps ≈ [10 .. 85] min
OT_2 (flash_memory) = M_2 / BW_{RR} = 4Mb / [8 .. 64] bps ≈ [0.75 .. 6] days
OT_3 (flash_disk) = M_3 / BW_{ECG} = 8Gb / [8 .. 64] bps ≈ [4.25 .. 42] years

22.5 WIRELESS MOBILE DEVICES FOR M-HEALTH

The WBAN Personal Server application can run on a wireless handheld device, such as smart phones (tend to be voice-centric devices with PDA-like data capabilities) or WWAN-enabled personal digital assistants or personal communicators (tend to be data-centric devices with voice capabilities). In home monitoring settings the Personal Server application may also run on a home personal computer. Each new generation of wireless handheld devices includes more processing power, more storage, and longer battery life, so that their capabilities meet the requirements of the Personal Server application. Consequently, the focus of this chapter is on Personal Server application requirements.

The Personal Server provides user interface, controls the WBAN, fuses data and events, and creates unique session archive files.

The Personal Server begins a health monitoring session by wirelessly configuring sensor parameters, such as sampling rate, selection of the type of physiological signal of interest, and specifying events of interest. Sensors in turn, transmit pertinent event messages to the Personal Server. The Personal Server must aggregate the multiple data streams, create session files and archive the information in the patient database. Real-time feedback is provided through the user interface. The user can monitor his / her vital signs and be notified of any detected warnings or alerts.

The user interface must provide seamless control of the WBAN, implementing all the necessary control over the WBAN, such as node identification, sensor configuration [53], sensor calibration, visual real-time data capture, graphical presentation of events, alerts, and health status.

Sensor node identification requires a method for uniquely identifying a single sensor node to associate the node with a specific function during a health monitoring session. For example, a motion sensor placed on the arm performs an entirely different function than a motion sensor placed on the leg. Because two motion sensors are otherwise indistinguishable, it is necessary to identify which sensor should function as an arm motion sensor and which sensor should function as a leg motion sensor. The Personal Server application will typically guide a user through the process of sensor mounting and setup.

Another important function is sensor calibration that can be permanent (once in a lifetime) or session specific (e.g., activity sensors on the leg may require an initial calibration of the default orientation on the body).

The personal sever is solely responsible for collecting data and events from the WBAN. Each sensor node in the network is sampling, collecting, and processing data. Depending on the type of sensor and the degree of processing specified at time of configuration, a variety of events will be reported to the Personal Server. An event log is created by aggregating event messages from all the sensors in the WBAN; the log must then be inserted into a session archive file. The Personal Server must recognize events as they are received and make decisions based on the nature and severity of the event. Normally R-peak or heartbeat events do not create alerts, and are only logged in the event log. However, the Personal Server will recognize when the corresponding heart rate exceeds predetermined threshold values; in that case it alerts the user that the heart rate has exceeded the target range.

Even in a deployed system where intelligent sensors analyze and process raw data, and transmit application event messages, there may be cases where it is necessary to transmit raw data samples. Such cases become apparent when considering a deployed ECG monitor. When embedded signal processing routines detect an arrhythmic event, the node should send an event message to the PS which will then be relayed to the appropriate medical server. The medical server, in turn, will provide an alert to the patient's physician. However, a missed heart beat can also be caused by electrode movement. Therefore, it would be useful to augment this event with actual recording of the fragment of unprocessed ECG sensor data. The recording can be used by a physician to evaluate the type and exact nature of the event or to dismiss it as a recording artefact. In such a case, the embedded sensor will begin streaming the real-time data to the Personal Server for a predefined time period.

22.6 NEXT-GENERATION M-HEALTH SYSTEMS

To gain wider acceptance the next generation of M-Health systems will have to address several challenges that today are limiting the usefulness of such systems. Those challenges include the availability of infrastructure and bandwidth in current and new wireless networks, miniaturization of medical sensors, convenience, and standardization of communication protocols and interfaces between medical and non-medical devices.

With the advances in wireless mobile devices, their usage in the M-Health context becomes more practical. A smart phone (see Section 22.5) seems to be the most frequently considered candidate for a future personal multimedia hub. In addition to handling all personal multimedia needs, it could also serve as a central part of M-Health systems by taking over the tasks of medical sensor coordination, monitoring, archiving, and reporting. The answer to the question why to use a phone as Personal Server seems to be an easy one to answer. The recent advances in computational and storage capacity, dramatic increase in the available wireless bandwidth, and the advances in screen technologies made it possible to turn a once simple device into a convenient do-it-all gadget. In addition, it appears that everyone has one now or will have one in the near future. While in 1991 there were only about 16 million cellular phone subscribers worldwide, by 2005, the number of subscribers had grown to 2.14 billion [58]. Worldwide cellular subscribers are expected to top 3.2 billion in 2010 and to continue to grow. In USA, the number of land lines reached almost 193 million in 2000 and it is declining since. At the same time, the number of cellular phone subscribers went from 5.3 million in 1990 to 202 million in 2005. [59]

22.6.1 Wireless Cellular Technologies for M-Health Systems

Despite the usual issues of concern whenever medical systems are considered (security, reliability, latency, physical size), one of the biggest obstacles to widespread use of cellular network in telemedical systems is the lack of bandwidth and performance.

There is some discrepancy in the way different groups classify current and future wireless cellular technologies into generations (1G, 2G, 3G, and 4G) [60][61]. We will give a short description of some of the most important technologies that are available today or currently being developed.

- 1G – The first generation of analog mobile phones, oriented exclusively to voice communication.
- 2G – This is a generation of phones that replaced the analog mobile phone of the first generation and it was primarily intended for digital transmission of voice. Three systems were developed – Pacific Digital Cellular (PDC, widespread in Japan), Interim Standard 95 (IS-95) and IS-136 in the United States, and Global System for Mobile Communications (GSM, widespread in European countries).
- 2.5G – This term is generally reserved for General Packet Radio Service (GPRS) delivered as a network overlay for GSM, CDMA (Code Division Multiple Access), and TDMA (Time Division Multiple Access) networks. While the basic GSM service allowed data rates of up to 9.6 kbps only, the GPRS is capable of having 14 kbps per channel (after protocol and error correction overhead). GPRS can combine up to eight channels, bringing the total to over 100 kbps in theory. For the first time, the focus of a wireless phone service was primarily on data transmission. The protocol architecture of the backbone network is based on the Internet Protocol (IP) which can be supplemented by the Transmission Control Protocol (TCP) for reliability or the User Datagram Protocol (UDP) for applications that do not require that level of robustness. The most important feature for end-users was the always-on connectivity of GPRS – the user can remain continuously connected but the network resources and bandwidth are used (and user is charged) only when data are transmitted. GPRS offered multiple services – web browsing, transfer of still images and video clips, document sharing and remote collaborative working, etc. All of these services allowed the emergence of first usable medical systems based on global availability.
- 2.75G – If the GPRS protocol was the first step towards 3G, the EDGE (Enhanced Data for GSM Evolution) protocol was the second one. In theory, EDGE offered data rates of up to 384 kbps, with the actual data rates being much lower. The real attractiveness of EDGE was in its ability to work on the existing GSM spectrum. The EDGE protocol was mostly adopted by mobile operators in countries where the allocation of spectrum for the 3G systems was delayed (for example in the USA).
- 3G – In 2000, European mobile phone operators spent well over $100 billion on 3G spectrum licenses. In the USA, in September 2006, the Federal Communications Commission (FCC) completed the auction of Advances Wireless Services (AWS) licenses in one of the bands (AWS-1). The total amount raised was close to $14 billion [62]. High fees and the necessity of building entirely new infrastructure delayed the introduction of 3G system, with the exception of some Asian countries (Japan, South Korea) where the fees were almost non-existent. The main air interface for the third generation is Wideband CDMA (W-CDMA). Two services using W-CDMA are UMTS (GSM successor) and FOMA (implemented in Japan). The International Telecommunication Union (ITU) approved UMTS as a part of the ITU-R M.1457 recommendation. UMTS provides up to 2 Mbps in indoor (low-mobility), up to 384 kbps outside (slow moving pedestrians), and up to 144 kbps for fast moving mobile phones.

The general idea behind IMT-2000/UMTS is to have a unified, seamless operation through the combined use of pico- and microcells indoors and in urban areas, macrocells in outdoor and rural areas, and satellite networks when necessary.

In the early days of defining the 3G systems, the video telephony was envisioned as the killer application. However, music downloading was the most frequently used service among the early adopters of these systems. It has been shown that 3G systems can easily support the amount of data required for medical applications [37].

Beyond 3G the requirements and classification become blurred. Instead of making a clear distinction between the systems, many use the term "3G and beyond" or B3G (beyond 3G) to include both 3G and 4G systems. As expected, some of the key requirements of new systems are the increased bandwidth, stable system performance, and the quality of service. However, the stress seams to be even more on providing a generalized access network that will allow internetworking between different access systems in terms of horizontal and vertical handover [63].

The following standards and technologies are by some considered as 4G systems, while the others are treating them only as the first steps towards the "real" 4G systems:

- HSDPA (High Speed Downlink Packet Access) is designed for data rates of up to 14.4 Mbps and features lower delays of approximately 100 ms. More importantly, in its initial implementation it is capable of delivering average throughput rates of about 1 Mbps. Cingular Wireless (in 2005) and a number of other companies (in 2006) offered HSDPA on a commercial basis. The peak network rates are expected to reach 7.2 Mbps by 2008.
- WiMax, originally based on the IEEE 802.16 specification, is designed to deliver up to 70 Mbps over a 50 km radius. The IEEE 802.16-2004 standard was delevoped for an unlicensed band (5.8 GHz) and primarily intended for local connectivity. The IEEE 802.16e-2005 added support for mobile radio operation. One aspect of WiMax that currently limits its usability is the fact that scheduling becomes inefficient if a large number of users is present in the same sector.

22.6.2 Future trends and obstacles

Most people agree that, to be considered as a "true" 4G system, the system has to be capable of achieving up to 100 Mbps when the user is stationary (indor/urban) and up to 1 Gbps when moving (outdoor). 4G system is data and visual-centric. In addition, a 4G system is expected to have the following features:

- IPv6 based: this increases the number of addresses, eliminates the need for NAT devices, etc. It would make it possible to use concepts and applications developed for other devices and easier integration in global systems.
- Multiple antennas at the transmitter and at the receiver are employed to sustain the increased data rate
- Support for Pervasive Networking (handover) as being defined by the IEEE 802.21 standard.

Some of the envisioned features beyond 4G include:

- Being able to smell the environment of the other person on the phone
- Communicating without emitting any voice (lips movement recognition)

Having in mind the current trends for increasing the data rates in new wireless mobile systems, it seems that the other obstacles to the widespread adoption of M-Health medical systems will become more important:

- The need for further miniaturization of medical sensors in order to increase the user's comfort, reduce the power consumption, and the possibility of unwanted disclosure of patient's condition.
- The lack of standardization and the ability to interface the existing medical equipment with the new communication systems
- The security of data during transmission and the security of data while stored in the user's personal hub (smart phone)
- User's and caregiver's confidence in M-Health systems.

22.7 SUMMARY

M-Health is becoming a major technological trend for ambulatory and prolonged physiological monitoring. It has the potential to shift the paradigm of healthcare from reactive to proactive, from disease management to disease prevention. System developers will still have to resolve a number of issues. The most important issues are: a) wearability and compliance, b) system integration, c) standardization of protocols and procedures, d) seamless system integration, and e) data mining of huge data sets.

In this chapter we have discussed the current state of technology, existing systems, and main issues to provide system designers a feeling of the "landscape" of the design space.

22.8 EXERCISES

1. Prepare a survey of relevant sensing techniques for non-invasive blood glucose monitoring used in commercial systems and research prototypes. Discuss their accuracy, system design, and suitability for wearable applications.

2. Prepare a survey of relevant sensing techniques for non-invasive blood pressure monitoring used in commercial systems and research prototypes. Discuss their accuracy, system design, and suitability for wearable applications.

3. Wireless interfaces consume the most of energy in WBAN sensor platforms. To reduce energy requirements (and consequently improve wearability), on-platform compression of biomechanical and bioelectrical signals can be employed. Prepare a survey of the existing approaches for compression of these signals and discuss their suitability for on-platform implementation.

4. A microcontroller system is performing the following task:

16-bit samples are sampled with a frequency f_{ADC}, processed, and stored in internal memory. After 16 samples are collected, they are sent using an external wireless interface operating at 200kbps. Data is encapsulated into a simple frame format:

Header (preamble + sync)	Sample 0	Sample 1	…	Sample 15	Checksum
6 Bytes	2 Bytes	2 Bytes		2 Bytes	2 Bytes

The microcontroller also keeps a software real-time clock with a 500µs precision.

The microcontroller is running at 8MHz (main clock), and the internal ADC is using the same clock. It takes:

- 8 clock cycles to sample a 16-bit data
- 13 clock cycles to convert it
- 14 clock cycles to process each sample and store it to memory
- 12 clock cycles to update real-time clock
- 12 clock cycles to prepare a byte and to send it to the external wireless interface

It takes 6 ms to wake up the wireless interface and to begin transmission. Assume that the microcontroller can wake up instantaneously and that the previously given processing times include interrupt overhead (if appropriate).

The current consumption of the microcontroller and the wireless interface is as follows:

Mode	*Current consumption*
Active mode, ADC turned off	2 mA
Active mode, ADC on	4 mA
Sleep mode	2 μA
Wireless interface, active mode	15 mA

If the system is running on batteries that have a capacity of 2000mAh, calculate the maximum sampling frequency (f_{ADC}) such that the calculated battery life is at least 6 months (180 days).

5. Calculate required bandwidth of a heart sensor that reports both raw ECG (1-channel) with sampling frequency of 100 Hz and heart rate, assuming average heart rate of 72 bpm. Heart beat stream includes 4-byte time-stamps.

6. Calculate required bandwidth for ECG and EEG monitoring. The system features 3 channels of ECG, 4 channels of EEG, and a tilt sensor. ECG and EEG signals are sampled at 125 and 250 Hz respectively, and tilt sensor is sampled once every 10 seconds and saved as one-byte status/position.

7. How many users with ECG monitors can we simultaneously monitor in a network with effective data bandwidth of 100 kbps? Each ECG monitor records three channels of ECG with sampling frequency of 500 Hz.

8. What is the expected operation time of a monitoring system with one ECG channel and two sensors with 3D accelerometers? Sampling frequency of the ECG is 250 Hz, sampling frequency of accelerometers is 40 Hz, and the personal server uses 512KB flash memory card.

9. What is the effective duty cycle of the above system assuming constant message size of 50 bytes with effective payload of 25 B, and 250 kbps wireless communication bandwidth?

10. What is the expected battery life assuming that the system is powered with 2 AAA batteries with capacity of 750 mAh. Average power supply current in active mode is 1 mA and during wireless communication 20 mA. The system features TDMA protocol with 50 ms time slots for each sensor. Each sensor listens throughout master time slot (50ms) and transmits in its own time slot. Average transmission time is 10 ms.

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