# Requirements and Design Spaces of Mobile Medical Care

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*Pervasive care and chronic disease management to reduce institutionalization is a priority for most western countries. The realization of next generation ubiquitous and pervasive healthcare systems will be a challenging task, as these systems are likely to involve a complex structure. Such systems will consist of various devices, ranging from resource-constrained sensors and actuators to complex multimedia devices, supporting time critical applications. This is further compounded by cultural and socio-economical factors that must be addressed for next generation healthcare systems to be widely diffused and used. These factors have a direct impact on the system and security models and will require further understanding to encourage users to embrace and adopt the new technology. These models must capture not only the perceived value of the new technology and its ease of use, but most importantly the perceived risk of using this technology. This paper outlines the design space of pervasive health monitoring with body sensor networks and derives the requirements for connected pervasive medical care systems. Commercial and academic mobile medical sensor systems have been mapped to the requirements derived and a comparative analysis of state of the technology is given.*

## I. Introduction

Advances in wireless sensor networking have opened up new opportunities in healthcare systems. The integration of existing specialized medical technology with pervasive, wireless wearable health monitoring sensors is pushing to new boundaries. Pervasive sensor technologies co-exist with the installed infrastructure, augmenting data collection and real-time responses. These sensors are particularly important to the world's increasingly aging population, whose health needs to be assessed regularly or monitored continuously. According to US census office, one third or more of the 78 million baby boomers and 34 million of their parents may be at risk for development of devastating chronic diseases [1]. These diseases include heart diseases & stroke, arthritis, diabetes, epilepsy, sleep apnea, asthma and allergies. Experts believe that presymptomatic testing could save millions of lives and money in the coming decades.

According to Centers for Disease Control and Prevention's (CDC) 'The World Health Report' [2], heart disease and stroke - the principal components of cardiovascular disease - are the first and third leading causes of death for both men and women in the United States, accounting for nearly 40% of all deaths. Over 927,000 Americans die of cardiovascular disease each year, which amounts to 1 death every 34 seconds. Although these largely preventable conditions are more common among people aged 65 years or older, the number of sudden deaths from heart disease among people aged 15-34 has increased.

In addition, more than 70 million Americans (over one-fourth of the population) live with a cardiovascular disease. Coronary heart disease is a leading cause of premature, permanent disability in the U.S. workforce. Stroke alone accounts for disability among more than 1 million Americans. Over 6 million hospitalizations each year are due to cardiovascular disease. The economic impact of cardiovascular disease on the U.S. health care system continues to grow as the population ages. The cost of heart disease and stroke in the United States is projected to be \$394 billion, including health care expenditures and lost productivity from death and disability. It has been suggested that this economic impact can be lessened and an increased lifespan of the humans can be achieved via pervasive monitoring of health indicators to detect diseases in early stages. Not only does it help reduce the effect of chronic illnesses, it also may potentially save lives.

Traditionally personal medical monitoring systems such as Holter monitors (a portable/wearable ECG device) can collect data for up to 24 hours. The recorded data is subsequently retrieved and analyzed by a clinician [3]. However their usage has been limited due to the following factors:

(a) It has been used only to collect data for off-line processing.

(b) Due to its numerous wires, rigid form, and adhesive electrodes, comfort is compromised, particularly while sleeping, making it cumbersome and unnatural for the user to wear continuously. The introduction of such unnatural variables can influence the wearer's natural behavior and skew results.

(c) Lack of integration of individual sensors.

(d) Interference on a communication channel shared by multiple devices.

(e) Nonexistent support for massive data collection and knowledge discovery.

(f) Due to the short duration involved and the unknown context within which the ECG signal is captured, reliable interpretation of the recorded data is always a challenge.

To address these drawbacks, several advanced ECG monitoring systems are emerging. In addition to off-line continuous data collection capabilities, they can also detect and signal a warning in real-time if any adverse event is captured [4]. Recent research has also focused on the development of body sensor networks (BSN) and pervasive monitoring systems for cardiac patients. For example, a number of wearable systems have been proposed with integrated wireless transmission, GPS (Global Positioning System) sensors, and local processing. Commercial systems which utilizes off the shelf mobile computing equipment such as PDAs (Personal Digital Assistants) or Smart Phones as mobile connected sensor hosts are also becoming available. For example, CardioNet [5] provides a remote heart monitoring system where ECG signals are transmitted to a PDA and then re-routed to the central server by using the cellular network. Such innovations in the market show that there has been an increasing interest in health monitoring among the wearable computing community.

It is desirable - if not required – to have a health monitoring system with the following characteristics:

- Accurately work for two-to-four weeks under continuous use (24/7) during active athletic and work situations as well as during sleep.
- Survive everyday use in low ($0^o$C) and high ($45^o$C) temperature environments.
- Small enough to keep the overall monitor height and footprint unobtrusive beneath clothing
- Non-irritating to the skin and hypoallergenic
- Non-invasive
- Consume less power and cost less.

Unobtrusive, wearable sensors will allow vast amount of data to be collected, and mined for next generation clinical trials. The implications and potential of wearable health monitoring technologies are paramount, since they will:

- *Enable* the detection of early signs of health deterioration.
- *Notify* health care providers in critical situations
- *Help* to find correlation between changes in physiological signals and lifestyle such as current activity, diet, exercise, stress levels, etc.
- *Provide* detailed information about physiological signals under various exercise conditions, thus bring sports conditioning into a new dimension.
- *Depreciate* the cost and inconvenience of regular visits to physician by facilitating automatic data collection and reporting. Therefore, many more study participants may be enrolled, benefiting biological, pharmaceutical and medical-applications research.
- *Transform* health care by providing physicians with multi-sourced, real-time physiological data. The data collected from the wireless sensor network can be stored and integrated into a comprehensive health record of a patient. This will help a physician to make more informed diagnosis.
- *Reduce* the human resources required for 24 hour physical monitoring, thus significantly reduces the human labor cost.
- *Bring* healthcare to remote locations and developing countries where cellular phones are pervasive.
- *Enhance and support* quality of life issues such as privacy, dignity and, convenience by providing services in the patient's own home.
- *Promote* healthy lifestyles thorough continuous health monitoring.

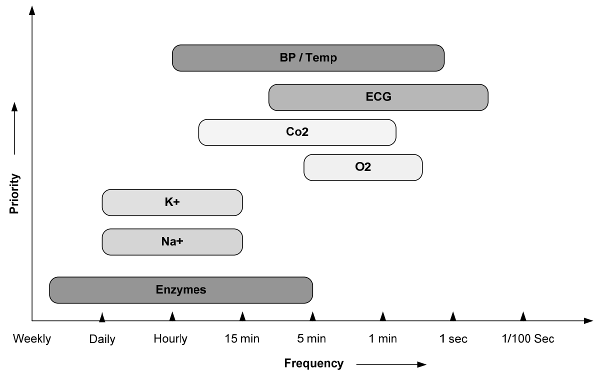


Figure 1: Typical priority and time requirements in clinical measurements

There are many sensors available for monitoring various physiological signals. Some of the most commonly used sensors in unobtrusive ubiquitous health monitoring include:

- Pulse oxygen saturation sensor, a non-invasive method for determining the percentage of hemoglobin (Hb) saturated with oxygen (SpO2) and Heart rate (HR)
- Blood pressure (BP) sensor
- Serum glucose level
- Electrocardiogram (ECG) sensor for monitoring heart activity
- Electro-myogram (EMG) sensor for monitoring muscle activity
- Electro-encephalogram (EEG) sensor for monitoring brain electrical activity
- Temperature sensor: Core body temperature and skin temperature
- Acceleration sensors which provide information on the activities of the wearer.
- Breathing sensor for monitoring respiration

In Table 1 and Table 2, we provide a summary of various sensor technologies along with their typical uses. Clinical practices require that each of these sensors measure vital signals at specific intervals that can span from a second to a week. Figure 1 shows the typical time requirements and relative priority of some vital body signs including BP, oxygen and carbon dioxide saturation in blood ($O_2$ and $CO_2$), heart condition and enzymes [6].

Today's technology provides the means of deploying advanced mobile health systems that are largely driven by the developments in wireless communications, pervasive and wearable technologies. Patients benefit from improved health as a result of faster diagnosis and treatment of diseases. This paper discusses the important dimensions of mobile medical care design space. Boundary conditions surrounding the design space for mobile health sensors are discussed along with a review of existing mobile sensor technology. In section 2, we will derive the design constraints and thus the requirements for biosensors and sensor networks. In section 3, we will review state of the technology mobile health care systems in the light of the requirements surrounding the design space.

## II. Design Spaces

Mobile sensor research has been mainly motivated by military and healthcare applications. More recently, a number of civilian applications of mobile sensors, notably in agriculture, environmental monitoring, logistics, security etc. have been deployed. While each sensor is usually customized for the application, we can show by example that mobile sensor networks are essentially a network of heterogeneous sensor nodes.

### II.A. Biosensor design

Technological advances in semiconductor and communication technologies have enabled development of body sensor networks that employ intelligent sensors which communicate wirelessly over the internet with personal and medical servers. These networks generally tend have a multi-tiered system architecture. Figure 2 shows an example of a body sensor network employing wireless sensors that communicate with a personal server (PDA) at the first level using Bluetooth or Zigbee protocols. The PDA can then communicate with medical servers over the internet using GSM/GPRS cellular networks at the second level, while at the third level, hospitals, emergency services, physicians and nursing homes are connected using a network of remote healthcare servers and databases. The requirements for a medical networked sensor system depend greatly on the specific application and deployment environment. A networked sensor system designed for ad hoc deployment in an emergency situation will have very different characteristics than one being deployed permanently in a hospital. For example, the permanent deployed system can make use of fixed, powered gateway nodes which provide access to a wired network infrastructure while the ad-hoc deployment may have to choose the gateway among sensor nodes using some leader election algorithm. De-

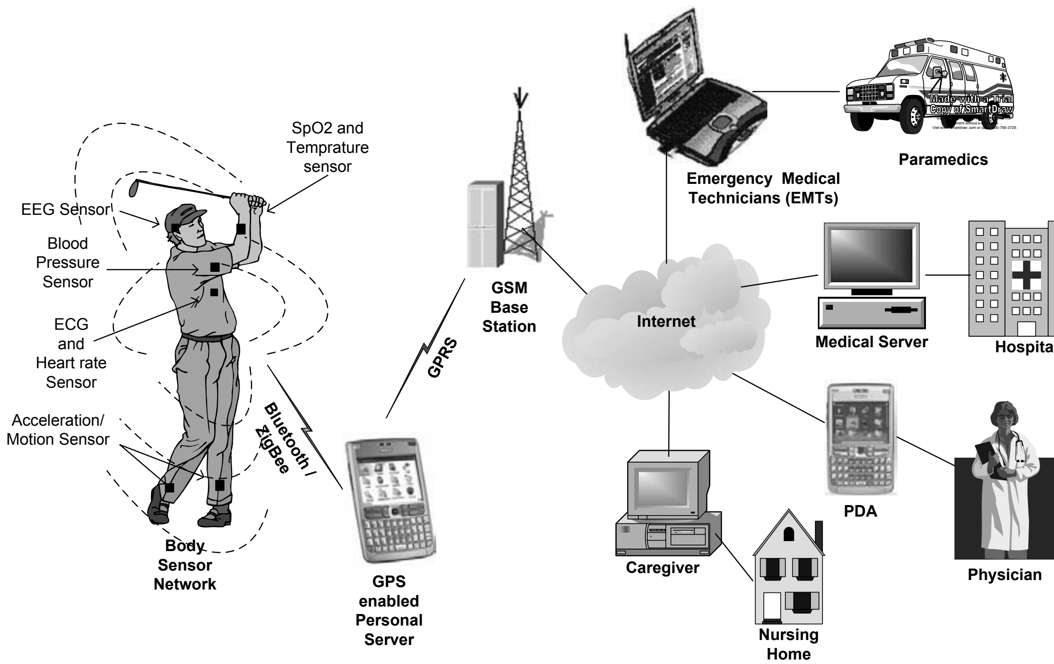


Figure 2: Wireless body sensor network for pervasive health monitoring

spite the argument above emphasizing the importance of problem domain in the design decisions of medical sensor networks, we can identify several design constraints that nearly all medical sensor networks would share. It is certainly a matter of debate to decide which issues are important enough to be considered as dimensions in the design space. In the next section we provide a list of boundary conditions surrounding sensor selection and design. One could argue in favor of adding more dimensions or reducing the ones detailed below. The design space will evolve as the applications and fields for the mobile sensor research progresses. The goal of this paper is to present a suitable set of dimensions based on two important principles. First the dimension should have a major impact on the design & implementation and secondly, the design dimension should be distinctive allowing sensors or applications to be classified. As a result sensor applications should have significant differences amongst themselves.

In mobile health care systems, the most important part is the biosensor since it is the basis for clinical diagnosis. At the physical level, the biosensor is the most widely deployed element. Therefore, factors which influence the biosensor design are of prime concern in mobile health care systems. Recent advances in biological, chemical, and electrical sensor technologies have led to a wide range of wearable and implantable sensors suitable for continuous monitoring. In the next sections we will derive and discuss the requirements for bio-sensors in pervasive health-care applications.

### *II.A.1. Non -intrusive*

In pervasive sensing and monitoring, the appearance of the sensor is an important factor. In many applications, such as nursing and in-home monitoring, the presence of the system should be undetectable to the user. Stealthiness is an important factor where intrusive technology may not be tolerated. It is also more socially acceptable and dignified to have less attention drawn to the sensors. However, there is some concern if this promotes unwanted surveillance and privacy issues.

An additional benefit for using non-intrusive sensors in health monitoring is that it allows for constant access to the user's vital signs, both day and night. This would enable computing the user's baselines for each physiological signal, to make the detection of anomalous events more meaningful and accurate.

### *II.A.2. Lightweight and Portable*

It is highly desired that pervasive non-intrusive sensor systems are lightweight for a good comfort level of the user. To be unobtrusive, the sensors must have a small form factor so that it can be worn by a patient on his/her wrist [7]. Several studies address sensors that can be embedded in garments [8] [9] and easily worn or hidden.

Advances in the MEMS (Micro-Electromechanical

Systems) technology have facilitated the development of miniature sensors in health monitoring applications. Almost all projects in the last five years use 3D accelerometers or combination of accelerometers, gyroscopes and GPS as context awareness sensors [9] [10]. Such MEMS are much light in weight, compact in size and consume very low power for their operation.

### *II.A.3. Power consumption*

The power source is one of the key elements effecting boundary conditions in pervasive sensing and computing. It is one of the major factors contributing to the overall size, weight and lifetime of the sensor. Requirements for extended battery life contradict the requirements for small form factor and low weight. This implies that sensors have to be extremely power efficient, as frequent battery changes for sensor would likely hamper users acceptance and increase the cost. So far, the battery has been the only reliable source of energy for sensor nodes.

Using a battery needs careful analysis of power consumption by the sensor node. Various factors contributing to the power consumption are:

- *Duty Cycle:* Sensors with different priorities and operational duty-cycles have different power needs. Duty cycles need to be appropriately selected for different sensor nodes depending on the application to maximize the lifetime of the sensor.

- *Communication Links:* Compared to wired communication channels, wireless communication links are more expensive in terms of power consumption. However wireless communication links provide ease of deployment and therefore reducing power consumption of the RF transceivers could significantly cut down the power consumption and extend the lifetime of the sensor node. FCC currently allocated the frequency range of 402-405MHz for medical implant communication services (MICS), and the frequency ranges of 608-614MHz, 1395-1400MHz and 1427-1432MHz for medical telemetry [11].

- *Sensor Intelligence:* Intelligent on-sensor signal processing has the potential to save power by transmitting only the processed data rather than the raw data, and consequently extend battery life. This also allows the sensor to have a lower duty cycle since data does not need to be continuously transmitted.

- *Security:* Data transmitted by a sensor node needs to be encrypted using algorithms that require computational power. If the encryption algorithm is more complex, it takes more computational power and thus affects the battery life.

A careful trade-off between communication and computation is crucial for an optimal power efficient design.

### *II.A.4. Deploying the Sensor : Location and Mounting*

The physiological signal being measured heavily influences the sensor location, but there seems to be some disagreement in the research community on the ideal body location of certain sensors. For example a motion sensor attached to an ankle is the most reliable single position for state recognition, while a combination of hip and ankle sensors discriminates the states even better [12].

Wrist worn devices can monitor most of the vital signals like pulse rate, BP, SpO2, etc. However measurements like ECG may be affected in the presence of a high level of measurement noise [7].

Although embedding the sensors into a garment could provide a convenient wearable system for patient, the design is not flexible for the addition or relocation of sensors [8].

## II.B. Sensor System

The sensor system is a synergy of emerging mobile medical computing, medical sensor technologies and communication technologies. A health monitoring system will have a network of sensors collecting data to be transferred to a processing unit for analysis. The network of sensors brings many different problems to manage such as sensor integration, configuration, deployment, data acquisition and communication, data privacy, software infrastructure and user interface.

Typical software architecture of a mobile medical care system is shown in Figure 3 which contains the sensor application, a gateway application and medical servers. The gateway application uses wide area communication infrastructure to communicate with medical servers which provide backend support at the healthcare service providers.

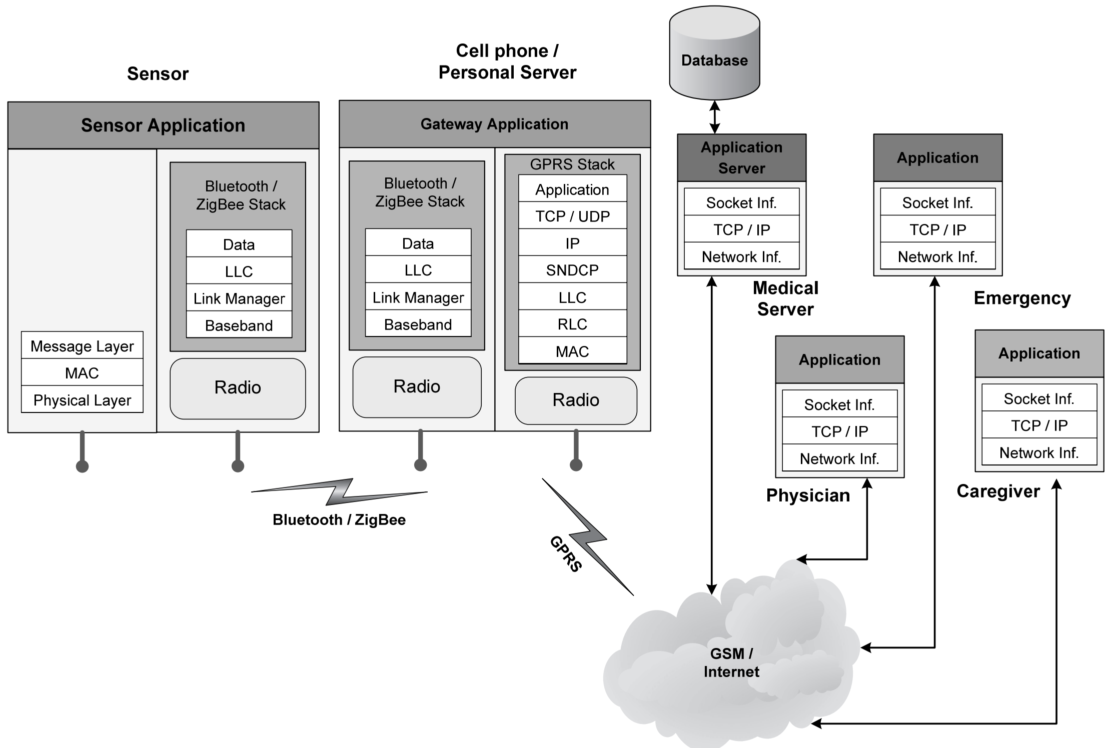


Figure 3: Mobile medical care system architecture and components

### II.B.1. Seamless System Integration and Configuration

Biosensors that address different monitoring requirements of patients can potentially be built by different vendors and may use different wireless protocols and technologies, each operating in a different part of wireless spectrum. In the absence of common standards, this can make integration and self-organization of body sensors extremely difficult. In order to interoperate in a single BSN, remote adaptation and reconfiguration should be an integral requirement of the system architecture.

A seamless system configuration should provide following benefits:

- Automatically install, self-activate, or even self-repair disparate medical devices and sensors with new services and/or applications remotely. This eliminates manual intervention.

- Allow dynamic configuration, reconfiguration and/or customization of new biosensors according to the monitoring needs of patients and health providers through service discovery protocols. This also provides the necessary authority to a health provider to configure and control the operation of the different biosensors in BSN.

- Enable applications to be dynamically updated in a sensor device or enable new features that improve the quality and reliability of the medical device.

In addition to integrating different sensor platforms, the system itself should integrate with existing medical practices and technologies. A simple measure of complexity would be the different types of sensors integrated into the system. Almost all the systems compared in Table 3 and Table 4 consider these criteria in their implementation.

### II.B.2. Real time data acquisition and analysis

In most sensor applications, the patient's physiological data (raw and extracted medical parameters) is transmitted to a medical server where more computational power and storage capacity is available. This data is usually transferred at periodic intervals and analyzed by the service provider. For such a sensor system the frequency of data collection is much higher than in many environmental studies. Since emergencies and health risks can occur at any time, it is necessary that the data is captured in real time and analyzed in real time as well. Efficient communication and real-time data processing is essential. It is worth noting that due to intermittent communication and message retransmissions the medical server will have to process out of order messages. Therefore, event ordering, time-stamping and, synchronization is necessary to have a feedback response in real-time.

### II.B.3. Multi-tiered data management, data mining

Data retrieved from body sensors are numerous and abundant. This streaming data has to be managed and integrated with existing types of medical information such as electronic medical records (EMRs), laboratory results, procedures, medical documents, and medical images in a logical and intuitive way.

Sensor data may be collected and integrated at multiple levels in the system. Data can be filtered at the sensor, correlated across multiple nodes or compressed for network storage. At each level, real time databases can be queried to collect data of interest. Usually the data collected from the sensor is relayed to the medical server which processes and analyses the data. If the link with the medical server is interrupted for any reason, the user can be notified of the error. For non time sensitive or non critical applications, the data can be stored on the sensor and sent when the communication link is established [7].

Data management and mining is required at every level of the sensor system.

### II.B.4. Deployment

The deployment of mobile medical sensor system may take several forms, two of which are sensor deployment and system deployment. In most cases, sensor deployment is manual where a health provider or trained personnel physically installs the biosensor. However the system can be deployed manually or automatically. The system here refers to a collective set of sensor nodes. Although each individual sensor may need to be deployed by a trained healthcare professional, the collective behavior of these sensors such as forming a cluster, leader election, peer-to-peer communication are desirable to be automated. In manual deployment, the network of sensors has to be created or augmented via manual intervention, particularly in nursing homes or at-home monitoring. Ad-hoc networks allow the system to be deployed automatically through peer to peer technologies and discovery protocols [13]. The ad-hoc network features are very important to emergency medical technicians (EMT).

Sensor deployment may be one-time activity, where the installation and use of sensor system are strictly separate activities. However, deployment may also be a continuous process, with more nodes being deployed at any time during the use of sensor system for example, to replace failed sensor nodes specifically in hospital settings where environmental monitoring is part of the health monitoring system

The actual type of deployment affects sensor node density, node locations and degree of node dynamics.

### II.B.5. Health Data Services

Sensor networks can support two types of health data services:

(1) Upload data services: These services are the basic services of any sensor network. They allow sensor nodes to collect and upload the patient's physiological data to the health provider. The physiological data is collected by periodically monitoring the body sensors and uploading this data to health provider's medical server. The data is then analyzed by the health care provider to provide feedback to the medical service provider (using download data service) if required.

(2) Download data services: These services are used for health information transmission from the medical server to the sensor device or recalibrate the sensor device. The downloaded information is particularly useful for chronically-ill patients that need regular feedback about their health and vital body signs. Other than health information, download data may also include software modules (e.g. updates or upgrades), new applications (e.g. micro browser, tools), or even content (e.g. video or jpeg images) for the device.

### II.B.6. Computational power

Sensor nodes, by design, have very limited computational power due to on-board power conservation requirements. Traditional security and encryption techniques, which are highly complex algorithms, are not well-suited for this domain. There is no known practical means of establishing encryption keys, although secret-key cryptographic systems have been demonstrated on wireless sensor device such as the Berkeley MICA "motes" [14].

### II.B.7. Software Complexity

The existing software for sensor nodes is very low-level and does not provide higher-level services such as discovery, naming, security, and data delivery within a common framework. A flexible protocol suite would be needed for integration of different wireless devices in a critical situation. The sensor nodes are usually compact operating systems with small footprints, while the MS can have high level OSes with multi processing capabilities.

Software complexity affects computational power and ultimately power consumption as complex algorithms require more computations. Large computational requirements increase battery size and overall system size and weight. As a consequence, the user's acceptance will be significantly reduced.

### II.B.8. Data Privacy and Security

Physiological data collected by the sensor network involves personal information whose privacy must be protected. It is likely that the healthcare provider owns the sensor infrastructure, yet the data pertains to the patient. Patient data must be readily accessible during emergencies and accesses to sensitive information should leave a non-repudiable [15] "trail". Any access mechanisms should be carefully designed to prevent theft of personal information. At the same time, it should be possible to filter out contaminated data. For example, the system should not "transpire" information when a patient walks into a wrong room since the patients privacy may have been breached.

Besides obvious security considerations with sensitive patient data, medical devices must meet the privacy requirements of local laws. For example, 1996 Health Insurance Portability and Accountability Act (HIPAA) in the US and/or the data-protection ACT 1998 in the Europe. Use of public and private key encryption are addressed in several recent studies. In TinyECC [16] authors report running times of 6.1 seconds for signature generation and 12.2 seconds for signature verification using 160-bit keys, on the 8-bit Atmel ATmega128 CPU of Crossbows MICAz platform. In [17] authors present a protocol based on TinyECC for securely establishing a communication channel to a base station using ECC (Eliptic Code Cyrptology). In [18] ECC implementation on MICAz nodes with a performance of 1.96 seconds is achieved. We believe that the results reported in these early studies are very encouraging. However more research on private-key and public-key cryptography schemes for sensor networks is needed. Such encryption schemes must be integrated into an appropriate authentication and authorization framework.

The security requirements in brief are: (a) Secure communication links with healthcare providers (b) Robust network security (c) Secure sensing and monitoring devices (d) Stronger patient-provider authentication.

### II.B.9. Communication / Sensor network

The purpose of BSN is to provide an integrated hardware and software platform for facilitating the future development of pervasive health monitoring systems.

In medical settings, a major emphasis is placed on data availability. Data may not be always or continuously available as different devices will be on different duty-cycles, from always-on wired power units to tiny wearable units making communication more difficult. Due to diverse nature of sensor networks, communication between devices may occupy different frequency bands and use different communication protocols. For example, ISM (Industrial, Scientific and Medical) bands or unlicensed bands for general telemetry (Berkeley MICA motes). Other devices may use a FCC licensed band reserved for that purpose. Biomedical devices may also use the WMTS band (wireless medical telemetry services, at 608 MHz) to avoid interference in the crowded unlicensed bands [11].

To achieve a low price and high volume, wireless medical sensors will need to be based on standard wireless technologies. The most widely used commercially available technologies include Bluetooth and ZigBee. Bluetooth [19] is mature technology, offers high communication bandwidth of up to 1Mbps which is more than sufficient for most intelligent sensors. However, in spite of low-power modes, power consumption and complexity of protocol stack implementation is still a limiting factor for most BSN applications. ZigBee [20] is another wireless technology standard for low data rate, very low-power applications, with potential applications in home automation, industrial control and personal health care. The maximum data rate of 250 Kbps is still sufficient for intelligent health monitoring sensors. Other emerging wireless technologies are Ultra Wide Band [21] and WiMax [22].

As personal information is wirelessly transmitted between sensors, security and reliability are major issues in the design of BSN. The IEEE 802.15.4 standard for wireless sensor networks and ZigBee protocol has incorporated a security layer in the protocol design. The issues related to self-management, and self-organization based on light-weight network protocol requires more research in future.

### II.B.10. Data prioritization

In clinical monitoring, there are priority constraints on data services placed on the monitoring systems. Some physiological data have higher priority than others for example; abnormal ECG data which is a emergency situation gets higher priority over regular data for potassium ($K^+$) level in blood. The network must prioritize the transmission of the critical data. Existing wireless network provide only "best effort" service and do not explicitly provide for prioritized traffic, which is critical for medical applications [14].

#### II.B.11. Utilization of off-the-shelf components

To have a low cost sensor network, it is important to have an extensible architecture. Low prices will only be possible if off-the-shelf components are used in the design and not limited to specific sensors or manufacturers. This heterogeneous sensor network should exist on a unified hardware/software platform that keeps development costs low. At the same time, using off-the-shelf components can affect the sensor accuracy as specialized sensors may not be readily available. While designing an extensible architecture, there needs to be a tradeoff between accuracy, price and competition.

#### II.B.12. Intuitive and simple user interface

The sensor networks should be manageable using a simple user interface, preferably a mobile or handheld unit. BSN is mainly intended for monitoring chronically ill patients, majority of which are elderly patients. For such patients, the user interface should be very simple and intuitive. In general, the user interface should allow the user to interact with the network based on user privileges. For example, the patient may only need to check the status of each sensor and the vital parameters, while the medical service providers may need to see the patient history and network administration options.

### II.C. Overall system / other constraints

There are other factors which influence the overall system characteristics. These include the network coverage, size, data standards and applications, access control, environmental factors and cost. Although these are not limiting factors, they can play a significant role in the wide acceptance of mobile sensor networks.

#### II.C.1. Ubiquitous Coverage

The effective range of the communication technologies on sensor nodes defines the coverage area of the sensor node. The degree of coverage also influences data processing algorithms. For short range sensor nodes, the data is transferred to a local aggregation unit like a PC or network access controller. For such sensor nodes, the data processing algorithms can be very simple. For long range sensor nodes, especially with cellular communication technologies, the sensor nodes need to have more complex data processing algorithm for effective use of the data bandwidth. High coverage is always desirable for maximum mobility for patient. However, long range communication links are susceptible to intermittent uplink connectivity. Global connectivity is important for handling emergency situations.

In addition to coverage, the patient sensor networks require reliable, secure and time bound data delivery performance from the network. While cellular networks provide maximum coverage, these links are plagued by high and variable RTT (round trip time) and low bandwidth, stalls (due to loss of coverage and handovers) etc. Other competing technologies like Bluetooth, ZigBee offer better QoS but have limited coverage and thus less patient mobility.

#### II.C.2. Sensor network size

The number of sensor nodes in a body sensor network is primarily determined by the requirements of the network connectivity, coverage, health application and by healthcare providers. The sensor network can also contain different types of sensors for different patients. In general, the sensor network size is variable and therefore the network should be able to support a large number of sensor nodes. Such a sensor network should also be scalable when additional sensors are required.

#### II.C.3. Data transmission

Sensor data can be transferred to the health care provider using disparate technologies like cable, DSL, 802.11 WLAN standards, GSM/GPRS, UMTS and other local wireless wide area network technologies. Sensor networks can exploit the increase in coverage and bandwidth of 3G cellular technology to build the always-on wide area sensor network. For instance, 3G UMTS and CDMA EvDO networks can provide higher data rates than standard dialup modems. These mobile networks may allow real time patient monitoring with very wide area coverage. This allows the physiological data to be correlated easily with the patient activity, thereby enhancing the quality of medical care.

Since data transmission is susceptible to intermittent communication links, a reliable transmission and re-transmission protocol is required.

### *II.C.4. Role based access control*

Privacy and security concerns require that only certain individuals be allowed access to patient data for a particular purpose. For example, family members may monitor quality of care for nursing home residents; doctors may delegate access privileges to other doctors and nurses. The system may also have digital rights management where data can be only read but not copied or viewed but not saved. To prevent abuse, patients may be given the privilege only to read the sensor data but make no modifications.

### *II.C.5. Standardization*

Many value added services can be developed once the BSN sensors are deployed, specific to the patients need. However, to facilitate the interoperation of these services, it's important to develop standards to promote competition and reduce costs. Such standards should include hardware, software, interface, and health standards.

### *II.C.6. Diverse environments*

Mobile healthcare aims to provide pervasive monitoring of vital physiological data for patients outside the hospital premises. As a result, patient monitoring can be deployed in nursing homes, assisted living, at-home, outdoor etc. Each deployment is a unique environment for sensor networks. For example, data communication can be via different means at different locations and the sensor networks have to be deployed in a configuration suitable to that environment. Environmental factors will also influence the design of the sensors and networks.

### *II.C.7. Lifetime*

Sensor nodes will need to be replaced by their expected lifetime. Sensors could be single use, multiple use or reusable, depending on the design and application. To keep costs low, some of the sensors can be recalibrated, serviced and redeployed in the same or different environments, making them highly reusable. Reusable sensors need to be sanitized (both hygienically and electronically) between reuses.

The lifespan of the sensor is a tradeoff between cost, reliability, technology, and reuse scenario.

### *II.C.8. Cost*

Cost is one of the most important factors influencing BSN and sensor design. The cost of a single device could be very high to very low (for large scale sensor deployment with limited features). There are other factors that influence the cost like - location and mounting, infrastructure costs, maintenance, operational, marketing, royalties, competition, insurance, refills etc. Since sensor nodes are mostly un-tethered autonomous devices, their energy and other resources of sensors are limited by cost constraints.

## II.D. Quality of service requirements

These requirements may impact other dimensions of the design space such as connectivity and resources.

### *II.D.1. Reliability*

Since sensors are deployed for physiological data monitoring, they need to have a very low failure rate. They also need to have highly accurate measurements and alarm triggers. Sensors and other devices must be able to interoperate without affecting each other's performance. The overall system should be able to yield high-confidence data suitable for medical diagnosis.

### *II.D.2. Robustness*

The sensor network needs to continue functioning even if certain well defined failure occurs. A fault tolerant system is highly desirable and needs to be designed for sensors which monitor the most important physiological data like ECG, BP etc. The sensor nodes need to operate in diverse environments and they should be designed to withstand the operating conditions.

### *II.D.3. Tamper resistance*

Public networks are susceptible to deliberate attacks. Since most of the data transmission uses the internet at some point, the sensor networks may be vulnerable to attempts to modify or tamper with the sensor or the system. The system should prevent/discourage attempts to modify the sensor/system. The system should remain operational even when subject to these deliberate attacks.

In addition, the sensor itself may be subject to maltreatment. The sensor should be designed to be tamper resistant, hermetically sealed which reduces the possibility of fraud.

## III. Applications

In this section, we will review leading commercial and academic efforts for developing mobile medical care and map these systems to the requirements derived in this paper. We selected systems that are well documented and implemented as if prototypes. Some of the applications are field research, while others are actual commercial products and some are advanced research projects that use mobile health sensors as a tool. For classification, we have used the reported parameters that were actually used in practical settings and we have deliberately refrained from speculation as to what else could have been done.

Note that there are usually different technical solutions for a single application, which means that the concrete projects described below are only examples drawn from a whole set of possible solutions. However, these examples reflect what was technically possible and desirable at the time the projects were set up. Therefore, we have decided to base our discussion on these concrete examples rather than speculating about the inherent characteristics of a certain type of application. Table 3 and 4 classifies the systems reviewed according to the dimensions of the design space described in the previous section.

### III.A. AID-N

Advanced Health and Disaster Aid Network (AID-N) [13] is developed at The Johns Hopkins University Applied Physics Laboratory. The system facilitates communication between health providers at disaster scene, medical professionals at local hospitals, and specialist available for consultation from distant facilities. The system comprises three separate tiers: mote wristband with finger sensor, a tablet PC and a medical center.

A wearable mote (MICAZ) attached to the patient's wrist sense and record vital signs into an electronic patient record database. In addition to several sensors the mote contains an electronic triage tag which allows the medic to set triage color (red/yellow/green) of the patient. It replaces the paper triage tags that are commonly used by medic today to prioritize the patients. The mote forms an ad-hoc wireless network with the first responder's portable tablet PC.

Sensors are integrated with pre-hospital patient care software - MICHAELS. The software is modified to automatically record and analyze the patient's vital signs and alert the first responder of any abnormal changes. A CDMA based EvDO wireless technology has been used for data transmission between tablet PC to medical center. A secure web portal allows authenticated users to collaborate and share patient's database in real-time.

The system is capable of measuring HR, BP, SpO2, body temperature, patient's activity and indoor/outdoor location. GPS provides geo-location and the indoor detection system (based on the MoteTrack project developed at Harvard Univ.) provides location where the GPS signals are unreachable. Although during the research some difficulties with sensors instrumentation design have been reported, the system can be useful for medics for patient monitoring and tracking in case of emergency situation.

### III.B. AMON

AMON [7] is the advanced care and alert portable tele-medical MONitor project financed by the EU FP5 IST program. It is a wearable (wrist-worn) medical monitoring and alert system that targets high-risk cardiac/respiratory patients. The system comprises two separate parts: a wrist-worn unit (WWU) and a stationary unit at telemedicine center (TMC).

AMON provides continuous collection and evaluation of multiple vital signs, online analysis with emergency detection via a rule-based approach with well defined heuristics and a cellular connection to the TMC. It features a flexible communication channel that can use a direct connection as well as short message system (SMS) services. In the event of a failure to initiate communication with the TMC, for non-critical situations the data can be stored (up to 4 days) on device and send when communication is restored, and the user is informed appropriately. The AMON system is capable of measuring BP, SpO2, one lead ECG and activity recognition, all in a single device. The authors carried out medical trials on 33 patients that highlighted some problems with the prototype but also validated the feasibility of the concepts and solutions adopted by the project.

### III.C. CodeBlue

CodeBlue [14] is a wireless infrastructure intended to provide common protocol and software framework in a disaster response scenario. The architecture was developed at Harvard University which allows wireless monitoring and tracking of patients and first responders.

The system integrates low-power wireless wearable vital sign sensors, handheld computers and location tracking tags. The CodeBlue software framework provides protocols for resource naming and discovery; publish/subscribe multi-hop routing, authentication and encryption provisions. It also offers services for credential establishment and handoff, location tracking, and in-network filtering and aggregation of sensor-produced data. A simple query interface allows emergency medical technicians (EMT) to request data from groups of patients.

The project research interests targeted the following areas:

- The integration of medical sensors with ultra low power wireless networks.
- Wireless ad-hoc routing protocols for critical care; security, robustness, prioritization.
- Hardware architectures for ultra-low-power sensing, computation, and communication.
- Interoperation with hospital information systems; privacy and reliability issues.
- 3D location tracking using radio signal information.
- Adaptive resource management, congestion control, and bandwidth allocation in wireless networks.

CodeBlue is designed to scale across a wide range of network densities, ranging from sparse clinic and hospital deployments to very dense, ad hoc deployments at a mass casualty site. It also operates on a range of wireless devices, from resource-constrained motes to more powerful PDA and PC-class systems.

### III.D. HealthGear

HealthGear [4] is designed as real-time wearable system for constant monitoring, visualizing and analyzing the user's SpO2, HR, plethysmographic signals and location information available in the cell phone. It was developed at Microsoft Research which consists of a set of non-invasive biosensors wirelessly connected via Bluetooth to a cell phone which stores, transmits and analyze the physiological data and presents it to the user.

There are mainly three parts in the system: Sensing module, Oximeter and a cell phone. The sensing module comprises DSP unit, Bluetooth module and batteries. The central processing unit in the system is an Audiovox SMT5600 GSM cell phone, running Microsoft Windows Mobile 2003 OS. HealthGear is implemented as a Windows Mobile application, with all its modules (sensor data reception, analysis, display and storage) running simultaneously in real-time on the cell phone. The current implementation includes an oximeter, but the system architecture allows for any number of sensors of heterogeneous nature.

The system was tested on subjects with sleep apnea. For automatic detection of sleep apnea events, two algorithms were developed. The first algorithm 'Multi-threshold time analysis' operates in the time domain, while the second 'Spectral analysis' operates in the frequency domain. The authors reported the results from a sleep study on 20 participants, which validated the feasibility of the concepts and solutions adopted by the project.

### III.E. LifeShirt

The LifeShirt [8] System by VivoMetrics [23] is a miniaturized, ambulatory version of an in-patient system. The system consists of the LifeShirt garment, data recorder, VivoLogic analysis and reporting software.

The LifeShirt is a lightweight, easy to use shirt with embedded sensors. To measure respiratory function, sensors are woven into the shirt around the patient's chest and abdomen. A single channel ECG measures heart rate, and a three-axis accelerometer records patient posture and activity level. It also correlates data collected by optional peripheral devices that measure blood pressure, blood oxygen saturation, EEG, EOG, periodic leg movement, core body temperature, skin temperature, end tidal $CO_2$, and cough.

The system collects, analyzes the data, and then integrates subjective patient input from an on-board digital diary. Results can be viewed in form of waveforms or as summary reports. The system includes an integrated PDA that continuously encrypts and stores the patient's physiologic data on a compact flash memory card. Data can be uploaded via the Internet or data cards can be sent to the VivoLogic data Center, where analysts and database specialists process and use the information for diagnosis.

The LifeShirt has been used in clinical trials and research. It is available as a commercial prescription medical device.

### III.F. m-health

M-health [24] integrates mobile computing, medical sensor, and communication technologies for mobile health applications. Wireless Body Area Network (WBAN) of intelligent sensors represents an emerging technology for system integration with great potential for unobtrusive ambulatory health monitoring.

The lowest level of data flow hierarchy of m-health consist of intelligent physiological sensors integrated into WBAN for example, ECGs, EMGs, EEGs, motion sensors, etc called as sensor node (SN). All messages from SN are collected by network controller (NC) and processed on personal server (PS). A personal server application can run on a PDA, cell phone or home personal computer. Typically all messages from SN are saved and retransmitted to the medical server (MS). Communication between PS and internet gateway is accomplished using standard WLAN and WAN technologies, GSM/GPRS, UMTS and other wireless local and wide area network technologies.

### III.G. MobiHealth

The MobiHealth [25] is a European Union project aims to provide continuous monitoring of patients outside the hospital environment. MobiHealth targets the introduction of new mobile value added services in the area of health, based on 2.5/3 G GSM/GPRS/UMTS technologies. They propose on integration of sensors and actuators, to a wireless BAN. MobiHealth targets improving the quality of life of patients by enabling new value added services in the areas of disease prevention, disease diagnosis, remote assistance, clinical research, physical state monitoring (sports) and even clinical research.

The goal of the MobiHealth project was to test the ability of 2.5/3G infrastructures to support value added healthcare services. For this a number of trials were organized spanning four European countries (Netherlands, Spain, Germany and Sweden) and covering a range of conditions like pregnancy, trauma, cardiology, rheumatoid arthritis and respiratory insufficiency. The analysis of results from these trials revealed technical issues related to UMTS networks performance. The most important issues reported are the restricted available data bandwidth for uplinks, delay variation, delays in transmission and handovers.

### III.H. UbiMon

UbiMon [26] is part of the UbiCare [27] centre, which is funded by the Department of Trade and Industry's (DTI) Next Wave research initiative in the UK. UbiMon aims to provide a continuous and unobtrusive monitoring system for patient in order to capture transient but life threatening events. With the current UbiMon structure, a number of biosensors including 3-lead ECG, 2-lead ECG strip, SpO2, sensors have been developed. To facilitate the incorporation of context information, context sensors including accelerometer, temperature, skin conductance and humidity are also integrated in BSN node.

The system comprises of five major components namely, the BSN nodes, the local processing unit (LPU), the central server (CS), the patient database (PD) and the workstation (WS). Apart from local processing LPU - a PDA device - it also serves as the router between the BSN node and the central server. The sensor data is collected and transmitted to CS via WiFi/GPRS network for long term storage and trend analysis.

## IV. Conclusion

Many patients can benefit from continuous monitoring as part of a diagnostic procedure, optimal maintenance of a chronic condition or during supervised recovery from an acute event or surgical procedure. Mobile medical sensors have great potential for continuous monitoring in ambulatory settings, early detection of abnormal conditions and, supervised rehabilitation. They can provide patients with increased confidence and a better quality life. They also promote healthy behavior and health awareness. Automatic integration of information from sensor systems into research databases can provide the medical community a possibility of data mining with huge amount of data. This will improve insights into disease evolution, the rehabilitation process and, the effect of drug therapy.

To achieve the level of robustness required for medical telemetry, significant research must be undertaken to design communication protocols, efficient energy-management schemes, and encryption algorithms. Tools and principles for selecting the right hardware components for specific applications would be desirable. Software support for the mobile sensors needs more research and is still at an early stage. In addition to these technical issues, economics of operating a mobile healthcare system also need to be analyzed carefully to ensure emergency and preventive healthcare monitoring is affordable to all levels of society. Major advances will be needed in the design space for wide acceptance of pervasive healthcare systems.

## V. Acknowledgement

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| Sensors | Functionality | Mesurement Method | Normal Reading Ranges | Related Diseases or Situations | Traditional Measuring Method | Emerging Technologies | Location and Mounting |
|---|---|---|---|---|---|---|---|
| Acceleration | Provide information on activity of the wearer, and context awareness | Non-invasive | Any activity | Fall / Unconsciousness of elderly person | Visual monitoring | 3D Accelerometer using MEMS | Attachments for Wrist or Waist or Legs. |
| Blood Pressure | Measure BP in arteries | Non-invasive | Systolic: $90<x<135$ mmHg Diastolic: $50<y<90$ mmHg | Hypertension, Hypotension, Strokes, Diabetes mellitus, Chronic Renal failure | Sphygmomanometer | Determination using red and infrared light passing through pulsating blood in vascular tissue. | Upper arm/cuff |
| Breath | Monitoring respiration | Non-invasive | $10<x<12$ BPM (Breaths per Min) | Hyperventilation syndrome, Respiratory sinus arrhythmia, Asthma, Lung diseases, Stokes | Stethoscope (manual testing) | Acoustic sensors | On temple or around the neck |
| Electro-cardiogram | To detect any heart problems or blockages in the coronary arteries | Non-invasive | Distinct pattern in waveform | Heart attack (myocardial infarction), Myocarditis, Pericarditis | 12-Leads and ECG machine | 1-Lead, 3-Lead and 5-Lead ECG | Affix the electrodes to specific points over the heart, chest, on the neck, arms and legs using gel |
| Electro-encephalogram | Monitoring brain electrical activity | Both Invasive and non-invasive | Distinct pattern in brain-wave | Stroke, Coma, Sleep disorder, Brain tumor, Alzheimer's disease, Psychiatric disorders | 8 to 20-Electrodes and EEG recorder | Noninvasive EEG using Alpha wave technology. | Affix the electrodes to scalp using adhesive gel |

Table 1: Commonly used Sensors in Pervasive Health Monitoring

| Sensors | Functionality | Mesurement Method | Normal Reading Ranges | Related Diseases or Situations | Traditional Measuring Method | Emerging Technologies | Location and Mounting |
|---|---|---|---|---|---|---|---|
| Electro-myogram | Monitoring muscle activity; Two types: Intramuscular EMG (invasive) and Surface EMG (non-invasive) | Both Invasive and Non-invasive | Silent at rest and Distinct pattern in waveform with muscle activity | Muscular dystrophy, Myasthenia gravis, Amyotrophic lateral sclerosis ALS), Inflammation of muscles | Needle and surface electrodes, Nerve stimulator, Amplifier with filters, oscilloscope, and device to store data, such as a magnetic tape recorder. | Respiratory muscle activity measured with a noninvasive EMG technique. | The muscles and nerves area that need to be tested |
| Heart Rate | Measure heart rate | Non-invasive | $60<x<100$ BPM (Beats per Min) | Heart attack (myocardial infarction), Myocarditis, Pericarditis | Stethoscope (manual testing) | Acoustic Sensors | On temple or around the neck or wrist or chest |
| Blood Oxygen Saturation | Determine the percentage of hemoglobin (Hb) saturated with oxygen | Non-invasive | $98\%<x<100\%$ | Asthma | Lancets, Test strips and oximeter | The red LED measures de-oxygenated hemoglobin and The infrared LED measures oxygenated hemoglobin | Attachments for Finger or Ear or Wrist |
| Serum Glucose | Measure serum glucose level | Invasive | $70<x<105$ mg/dL | Diabetes (Hyperglycemia and Hypoglycemia), Hepatitis C, | Lancets, Test strips and Glucose meter | Noninvasive based on thermal emission spectroscopy (TES) | Finger or Arm |
| Temperature | Two types: Core body and skin temperature | Non-invasive | $96$ F$<x<98.6$ F | Fever, Hypothermia | Thermometer - typically mercury or alcohol based | Non-touch infrared based digital thermometer | In the mouth (oral), armpit (axillary), eardrum (tympanic membrane) |

Table 2: Commonly used Sensors in Pervasive Health Monitoring

| Systems | Size and Weight | Power Requirement | Location and Mounting | Sensors integration | Data management | Health data services | On Board Computing | Privacy and Security | Communication | Qos |
|---|---|---|---|---|---|---|---|---|---|---|
| AID-N [13] | MICAz mote Small (5.8 x 3.2 x 1.5 cm) | MICAz-2 AA batteries, 5-6 days of continuous run, 6 hours in continuous mode. | Wrist-worn with finger attachment | Heart rate & SpO2-5 min , Blood pressure, Accelerometer, Location sensor (GPS & Indoor loc. sys)-5 min, Rel humidity, Temperature | 3-tiered: MICAz (NVRAM): 512kb, MICHAELS & MS | Up / download from/to motes from/to Tablet PC at 76.8 kpbs | NA | Authenticated, Low level built-in data security (802.11), secure, encrypted web services | CDMA EvDO; Ad-hoc network; CDMA Coverage dep. | Real time, MICAz motes, Content-specific data prioritization |
| AMON [7] | 286 g | Battery 1.25 AH LiION, Est. Run 2 days | wrist worn | Pulse and SpO2-2 min, Blood pressure & ECG , Skin temp, 2-axis Acceleration | 2-tiered: WWU (FLASH)-4 MB & TMC | Upload/ download from/to device from/to medical center | Conv. Algo for BP computation, Derivation of QRS width, RR distance, QT interval from ECG | Encryption & authentication (GSM /GPRS protocol) | GSM data link -SMS for BP results, Virtual ckt swithced comm for raw ECG data; GSM coverage dep. | Real time |
| CodeBlue [14] | 5.7 x 3.2 x 2.2 cm | MICAz-2 AA batteries, 5-6 days of continuous run | Finger attachment | Heart rate, SpO2, Plethysmographic signals | 3-tiered: Sensor node , PDA & MS | from/to motes from/to Tablet PC transfer at 76.8kpbs | Atmega128L or MSP430 | Authenticated, Lightweight PK based elliptic curve alg. | IEEE 802.11b, ad-hoc , Access points | MICA2 motes, Content-specific data prioritization |

Table 3: Commercial and academic mobile medical sensor systems have been mapped to the requirements derive

| Systems | Size and Weight | Power Requirement | Location and Mounting | Sensors integration | Data management | Health data services | On Board Computing | Privacy and Security | Communication | Qos |
|---|---|---|---|---|---|---|---|---|---|---|
| Health Gear [4] | NA | 2AAA batteries, 12 hours run time. | Finger attachment | Heart rate, SpO2, Plethysmographic signals | 2-tiered:Cell phone (RAM) 32MB and MS | Transfer from/to phone from/to center | 200 MHz ARM processor | NA | GSM/GPRS - data link; coverage dep. | Real time, OEM components |
| LifeShirt [8] [23] | Recorder: 5.4x3.25x 1.95, Data Cable 33.5 in | 24 hr use before recharging | In garment | ECG , Acceleration, BP, SpO2 & tidal CO2, EEG, EOG, core & skin temp | 2-tiered: Data recorder & Data center | Only upload from sensors to PDA and PDA to medical center | NA | NA | NA | NA |
| m-Health [24] | NA | Processing 1-10 mW, Idle $<100$ $\mu$W, comm. 20-50 mW | NA | NA | 3-tiered: WBAN , PS & MS stored in EMR | NA | 1-10 MIPS | Encryp. Authentication | WLAN, 3G GSM /GPRS, UMTS | NA |
| Mobi Health [25] | NA | NA | NA | Heart rate, SpO2, Blood pressure, Temperature, Motion/Activity, and Respiration | NA | Upload from/to MBU from/to MS GPRS & UMTS | NA | NA | GSM /GPRS & UMTS | NA |
| UbiMon [6] [26] | BSN node small (2.6x2.6 cm) or MICAz mote | For BSN node active: 616 $\mu$W & stand by:3.52 $\mu$W | Body | ECG , SpO2, Accelerometer, Temperature & Humidity sensors | 3-tiered: BSN node,LPU & Central server | Upload/ download from/to BSN nodes from/to LPU at 250kpbs | TI MSP430 16-bit RISC processor | Authentication | WiFi/GPRS network; Adhoc network; GSM | Real time, OEM, MICA2 |

Table 4: Commercial and academic mobile medical sensor systems have been mapped to the requirements derive