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Pervasive Healthcare and Wireless Health Monitoring

Upkar Varshney

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Abstract With an increasingly mobile society and the worldwide deployment of mobile and wireless networks, the wireless infrastructure can support many current and emerging healthcare applications. This could fulfill the vision of "Pervasive Healthcare" or healthcare to anyone, anytime, and anywhere by removing locational, time and other restraints while increasing both the coverage and the quality. In this paper, we present applications and requirements of pervasive healthcare, wireless networking solutions and several important research problems. The pervasive healthcare applications include pervasive health monitoring, intelligent emergency management system, pervasive healthcare data access, and ubiquitous mobile telemedicine. One major application in pervasive healthcare, termed comprehensive health monitoring is presented in significant details using wireless networking solutions of wireless LANs, ad hoc wireless networks, and, cellular/GSM/3G infrastructure-oriented networks. Many interesting challenges of comprehensive wireless health monitoring, including context-awareness, reliability, and, autonomous and adaptable operation are also presented along with several high-level solutions. Several interesting research problems have been identified and presented for future research.

Keywords mobile and wireless networks · pervasive healthcare applications · location management · ad hoc wireless networks

U. Varshney (✉)
Department of Computer Information Systems,
Georgia State University,
Atlanta, GA 30302-4015, USA
e-mail: uvarshney@gsu.edu

1 Introduction

The introduction of telecommunications technologies in healthcare environment has led to an increased accessibility to healthcare providers, more efficient tasks and processes, and a higher overall quality of healthcare services [1–6]. However, many challenges, including a significant number of medical errors [7, 8], considerable stress on healthcare providers, and a partial coverage of healthcare services in rural and underserved areas, still exist worldwide [9, 10]. These combined with an increasing cost of healthcare services, such as the cost of healthcare services reaching to 15% of Gross National Product for U.S. [1], and an exponential increase in the number of seniors and retirees in developed countries [11] have created major challenges for policy makers, healthcare providers, hospitals, insurance companies and patients. One challenge is how to provide better healthcare services to an increasing number of people using limited financial and human resources. The current and emerging wireless technologies [12, 13] could improve the overall quality of service for patients in both cities and rural areas, reduce the stress and strain on healthcare providers while enhancing their productivity, retention and quality of life, and, reduce the long-term cost of healthcare services [51, 53]. Many medical errors occur due to a lack of correct and complete information at the location and time it is needed, resulting in wrong diagnosis and drug interaction problems [7, 8]. The required medical information can be made available at any place any time using sophisticated devices and widely deployed wireless networks. Although, wireless technologies cannot eliminate all medical errors, but some of the informational errors can certainly be eliminated by such access to medical information. The wireless technologies can be effectively utilized by matching infrastructure capabilities to healthcare needs.

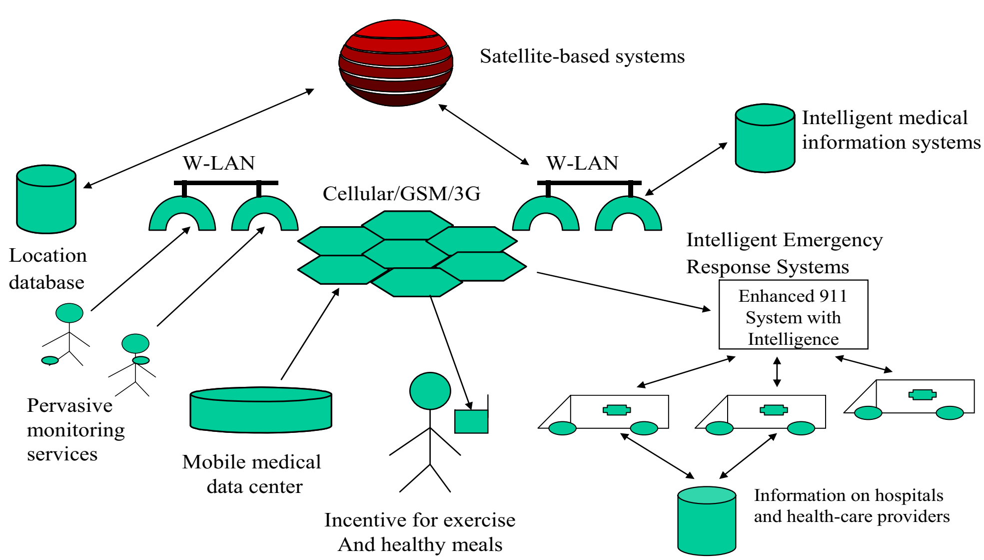
These include the use of location tracking [27–30], intelligent devices, user interfaces, body sensors [31–33, 38], and short-range wireless communications for health monitoring; the use of instant, flexible and universal wireless access to increase the accessibility of healthcare providers; and reliable communication among medical devices, patients, healthcare providers, and vehicles for effective emergency management. In the long-term, affordability, portability, and reusability of wireless technologies [18] for health monitoring and preventive care will also reduce the overall cost of healthcare services [12–15].

In this paper, we present a vision of pervasive healthcare that includes applications and requirements of pervasive healthcare, wireless networking solutions and several important research problems. We define pervasive healthcare as “healthcare to anyone, anytime, and anywhere by removing locational, time and other restraints while increasing both the coverage and the quality of healthcare”. This includes prevention, healthcare maintenance and checkups; short-term monitoring (home healthcare monitoring), long-term monitoring (nursing home), and personalized healthcare monitoring; and incidence detection and management, emergency intervention, and, transportation and treatment (Fig. 1). The pervasive healthcare applications include pervasive health monitoring, intelligent emergency management system, pervasive healthcare data access, and ubiquitous mobile telemedicine. The wireless networking solutions include use of wireless LANs, ad hoc wireless networks, cellular/GSM/3G infrastructure-oriented networks and satellite-based systems. Many important research problems have been identified and discussed for future work.

Now, we briefly summarize how wireless technologies have been introduced in healthcare. The use of wireless sensors in minimally invasive continuous health-monitoring systems is discussed in [13]. A maritime multilingual telemedicine system that uses satellite and ground-based networks for supporting audio and video-conferencing, and multimedia communications is presented in [16]. Several applications of wireless telemedicine systems including tele-cardiology, tele-radiology, and tele-psychology are presented in [14]. An implementation of pervasive computing technologies in an assisted-care facility (http://www.elite-care.com), where by using network sensors and databases, facility staff members are alerted when residents need immediate care, is presented in [17]. A wearable healthcare assistant has been designed to sense pulse waves, user’s actions, and postures, and to capture contextual photos and continuous voice. A high-pressure (stressful) state is detected from the high pulse-rate by using the acquired context information [19]. The information is stored and retrieved on a website and requires modification for fitting on smaller handheld devices. It has been shown that the elderly are ready to begin using wireless technologies as long as these truly facilitate independent living [22]. An overview of general issues in m-health can be found in [70]. A description of “Personal Wellness Systems” and related technologies and usage scenarios is presented in [74].

The above review of wireless in healthcare illustrates several issues including the preliminary introduction of wireless technologies without identifying healthcare requirements and challenges, limited utilization of the unique capabilities of wireless infrastructure, use of a single type of wireless network, thus restricting the access and coverage, and very fragmented use. To address these issues, we present a vision of pervasive healthcare that includes applications and requirements of pervasive healthcare, wireless networking solutions and several important research problems. The paper is organized as follows. Several pervasive healthcare services and their requirements are presented and

Figure 1 Several pervasive healthcare applications



discussed in section II. A major example of pervasive healthcare, called comprehensive wireless health monitoring, is presented in section III. Context-awareness and reliability of wireless health monitoring are addressed in section IV. The important research problems from technical, medical and management perspectives are identified and discussed in section V. The conclusion is presented in section VI.

2 Pervasive healthcare applications and requirements

The healthcare applications could be divided among the following categories: prevention, healthcare maintenance and checkups, short-term monitoring (or home healthcare monitoring), long-term monitoring (nursing home), personalized healthcare monitoring, incidence detection and management, and, emergency intervention, transportation and treatment. The advances in wireless and mobile technologies, such as the ability to store a significant amount of information on a mobile device, radio-enabled watches, and a grid of body sensors, can be used to facilitate these applications. A possible scenario is to store, and update as necessary, all the medical information on a user's mobile device, allowing critical information such as blood group, allergies, and existing medical conditions to be used in delivering urgent and correct medical care. In the near future, wearable and handheld devices could sense one or more vital signs and transmit alert messages to hospital, ambulance and healthcare providers for getting emergency services for the car driver going through a cardiac arrest. Then using efficient vehicular routing and information on nearby hospitals, patients can be treated immediately and many lives can be saved. In another scenario involving normal checkup, a patient could use her handheld device to upload the necessary medical and insurance information at the doctor's office, thus reducing the amount of efforts and/or inconsistency in entering detailed information.

In addition to the current applications such as mobile telemedicine, several new healthcare applications could become possible due to the wireless and mobile technologies (Fig. 1). Some of these applications are

1. *Comprehensive health monitoring services* would allow patients to be monitored at anytime in any location. Using his/her medical history and current conditions, one or more actions can be taken including sending an alert message to the nearest ambulance or a healthcare professional. Some intelligence in the form of context awareness can be built in pervasive services to avoid "false-positive" alerts. These services could reduce the time between the occurrence of an emergency and the arrival of needed help.
2. *Intelligent Emergency Management System* could be designed using the intelligence of and information from mobile and wireless networks. This system would be able to manage the large call volume received due to a single accident or incident and effectively manage the fleet of emergency vehicles.
3. *Health-aware mobile devices* would detect certain conditions by the touch of a user. Many of the portable medical devices can be integrated in the handheld wireless device. These would allow the detection of pulse-rate, blood pressure, and level of alcohol. With its analysis of known allergies and medical conditions, the device could alert healthcare emergency system (such as enhanced-911 in U.S.).
4. *Pervasive access to healthcare information* would allow a patient or healthcare provider to access the current and past medical information. And for healthcare providers, having access to current and complete information anytime anywhere would result in reduced number of medical errors. Also, a dynamic management of medical information could allow a patient to restrict who can access his/her medical information and for how long. Another application in this category can be "Mobile Healthcare Data Center" that can support a large amount of stored healthcare data to be made available to authorized "mobile decision makers" for making healthcare decisions. The data can also be made available to healthcare researchers without identifying the patients.
5. *Pervasive lifestyle incentive management* could involve giving a small mobile micro-payment to a user device every time the user exercises or eats healthy food. This mobile money can then be used for paying wireless monthly charges, for donating to a charity of user's choice, or for paying healthcare expenses. Such incentives can lead to healthier individuals and thus reducing the overall cost of healthcare services. The incentive management can be facilitated with wide-scale deployment of wireless LANs supporting mobile payments [23, 26].

2.1 General requirements

The general requirements of pervasive healthcare include:

1. High level of security by mitigating threats to healthcare data and abuse of benefits, encryption, authentication, and access control
2. High level of privacy in pervasive healthcare systems, which may become more aware of patient's behavior, habits, and movements, and supporting patient-selectable level of anonymity in pervasive healthcare services

3. The usability, reliability and functions of patient's device, portable or wearable
4. Highly reliable and usable wireless infrastructure that is accessible, supports prioritized communications, is always on by multi-network or redundancy, and has sufficient network resources for pervasive healthcare
5. A new business model that includes the initial cost of pervasive healthcare, different healthcare players and their roles, potential future savings and their utilization
6. Solutions of management challenges related to insurance payments and liability, the role and restrictions of regulatory frameworks such as HIPAA in USA, and, training and adoption of pervasive healthcare

2.2 Wireless requirements

The wireless requirements of pervasive healthcare services are comprehensive coverage, reliable access and transmission of medical information, location management, and support for patient mobility. Many of the existing and emerging wireless networks such as cellular-oriented (2G/3G/4G), wireless LANs, satellites, and short range technologies such as sensors, RFID, and personal area networks could support one or more of these requirements.

The wireless infrastructure used for pervasive healthcare should allow the use of several diverse mobile and wireless networks to support the requirements of healthcare applications. The wireless infrastructure should increase the access and quality of healthcare service by using location tracking, ad hoc networking, and wireless network intelligence. The coverage and scalability challenges should be supported to provide wireless coverage in both rural and urban areas covering both indoor and outdoor environments. This can be achieved by using public wide area cellular networks for urban coverage combined with wireless LANs for the congested indoor and outdoor urban areas. Additionally, to provide healthcare services in rural areas that are not covered (or have partial or unreliable coverage) by wide area cellular networks, the wireless infrastructure should include satellite and wireless LANs. This access to multiple wireless networks could enhance both the coverage and the scalability of wireless infrastructure in terms of users, distance, and applications.

Many of the healthcare applications would benefit form the location tracking of patients and healthcare providers, devices, and supplies. The location tracking can also be very helpful for finding people with matching blood groups, locating organ donors, providing post-op care for people, and helping old and mentally challenged people in hospitals and nursing homes. A comprehensive wireless architecture for location management in healthcare environment can be designed by utilizing one or more location-tracking technologies including GPS, E911 in cellular networks, wireless LANs, and RFID [24]. Each one of these supports location tracking of people, devices, and services at diverse location accuracy. The location precision achieved is in the range of a few to several hundred meters. The outdoor tracking support for healthcare applications may be provided by either a cellular/PCS system or a satellite-based system such as assisted GPS. Even wireless LANs and RFID-based systems could support applications requiring outdoor location management. Since many indoor tracking applications require higher location precision, smaller wireless local area networks (WLANs) and personal area networks (PANs) should be used for indoor location management. Indoor tracking for healthcare applications could be performed using specialized cells (where a base station can locate in a very small area, but a significant number of base stations are required to cover the whole area), wireless LANs, ad hoc personal area networks (PANs), and, Radio Frequency ID (RFID).

In general, wireless technologies should also reduce long-term cost of healthcare and would also result in an increased productivity of healthcare providers. This can be ensured by (a) improved coverage and scalability of wireless networks, (b) dependable and reliable operation, (c) practical, implementable and reusable wireless technologies, and, (d) expandable and modifiable wireless technologies for pervasive healthcare. In the next section, we present a major example of pervasive healthcare, called comprehensive wireless health monitoring.

3 Comprehensive wireless health monitoring

Worldwide, the number of people with a range of physical and/or cognitive disabilities has been growing and includes about 37 million people in US, or 14% of the population [55]. About 40% of US seniors experience one or more forms of physical and/or cognitive disabilities, and with the aging of US population the number will grow even more significantly in the future. It has been shown that health monitoring can reduce the number of readmissions for patients suffering from chronic health problems [67]. The monitoring can also help in keeping track of patients with one or more cognitive disabilities, such as the stray prevention system for elderly with dementia [69]. To support the long-term healthcare needs of the patients, comprehensive wireless health monitoring solutions must be developed for homes, nursing homes, and hospitals [41, 44, 45]. There are many challenges in designing and developing such systems, including diverse requirements of health monitoring, transmission of vital signs over limited and variable capacity wireless networks, and the medical decision making on the healthcare needs of the monitored patients (Fig. 2; [84]). The health monitoring in-

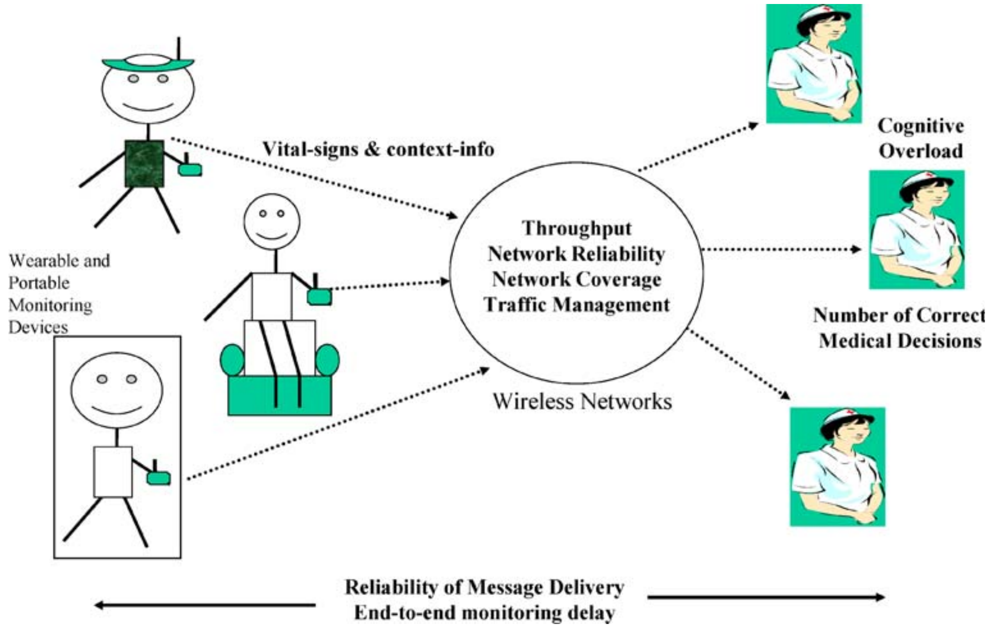


Figure 2 Comprehensive health monitoring

volves measuring multiple parameters simultaneously over a long term without disturbing the daily lives of the patients. In addition to vital signs, other health parameters can also be autonomously measured by embedding monitoring sensors in bed, toilet, bathtub, kitchen appliances among others [68]. The monitoring system should operate autonomously without requiring intervention. The comprehensive health monitoring system should also be context-aware, which will also aid in a better decision making by healthcare professionals on patient's current conditions and healthcare needs.

Wireless health monitoring involves measurement and digitization of vital signs [56], such as blood pressure (BP), Electrocardiogram (ECG), respiration rate, pulse, and oxygen saturation (SpO2) , transmission of packets over wireless networks, and delivery of medical information to healthcare professionals. The monitoring system should transmit both routine vital signs and alerting signals when vital signs cross one or more "individualized" thresholds. The vital signs are represented as analog signals along with their nominal values in Fig. 3. These vital signs are obtained, sampled, and digitized for transmission as network packets. The health monitoring device [57–59] can be wearable or handheld depending on the level of difficulty in use, portability, and the type of disability for the monitored patient. The device should operate autonomously and must send alarm signals when one or more problems arise. In addition to vital signs (Fig. 3), the following patient parameters must be monitored: skin breakdowns, gait and balance (to reduce number of falls), motor activity, agitation, current location, cigarette smoke, and the amount of moisture in clothes. The falls, common in the disabled, are known to significantly increase the risk of multiple long-lasting injuries and a

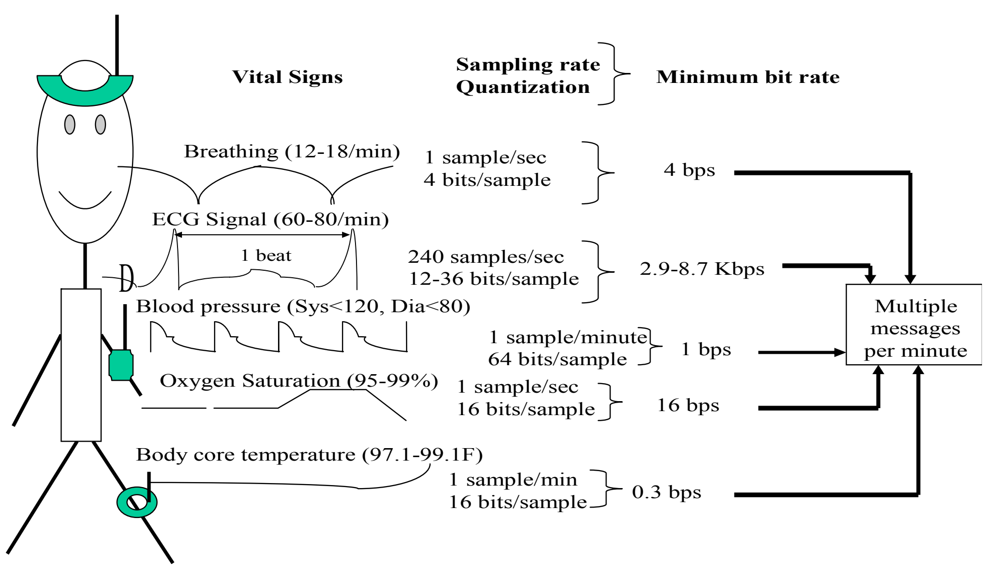


Figure 3 Vital signs and digitization

frequent hospitalization of longer durations. There has been some work in falls detection by using an array of infrared sensors [73].

The health monitoring of patients could generate a significant amount of network traffic depending on the number of patients, the diversity and the number of vital signs, the monitoring frequency, and representation of healthcare information. The total traffic could affect the achievable reliability of message delivery and the end-to-end monitoring delay. The traffic generated by vital signs can be compressed, however, increased processing and packet delays, and, potential for "introduced" errors in healthcare information must be carefully considered.

The end-to-end performance in wireless health monitoring can be improved by transmitting minimal real-time information, such as differential signals or changes since the last transmission, over the wireless network and utilizing stored knowledge on patient and medical advances. Also, the comprehensive monitoring can be supported by allocating higher priorities for emergency and crisis management combined with preemptive capability to terminate nonurgent traffic over wireless networks. The health monitoring traffic can be managed at multiple places including at the source device, in the network, and at the health professional's device.

3.1 The work related to wireless health monitoring

There has been some work in health monitoring including an implementation of infrared and radio-based locator badges [17], long-term health monitoring by wearable devices [34], wireless telemetry system for EEG epilepsy monitoring [40], ring sensor for blood oxygen saturation monitoring [42, 72], short range Bluetooth-based system for digitized ECGs [35], wearable stethoscope [36], and, real-time monitoring of patients in the home environment [39, 75]. Clothing-embedded transducers for ECG, heart rate variability, and acoustical data and wireless transmission to a server are proposed in [34]. A requirement model for delivering alert messages is presented in [43]. The use of wireless sensors in minimally invasive continuous health-monitoring systems is discussed in [13]. A design approach for ECG data compression for a mobile tele-cardiology model involved a significant compression ratio and reduction in transmission time over GSM network [47]. A telemedicine system that can "bring" an expert specialist doctor to the site of the medical emergency to evaluate patient data and issue directions to the emergency personnel on treatment procedures is presented in [48]. Various issues in pervasive healthcare are discussed in [49]. Personal health monitors based on a wireless body area network (BAN) of intelligent sensors are proposed for stress monitoring [50]. A health monitoring system, named WEALTHY, has been developed with yarns acting as sensors, electrodes, and connections. This can also have an embedded short-range wireless system for transferring signals to a PDA or mobile phone [71]. A preliminary work on proposed changes in network protocols for healthcare is presented in [76]. Use of ECG signals with GPS location data over GPRS networks in arrhythmia monitoring system is shown in [79]. Several commercial systems for remote heart monitoring using cellular-type wireless networks are described in [80]. A 3rd generation CDMA commercial system is utilized in transmitting video, audio, and patient's bio-signals from an ambulance [81]. A prototype of a wrist-worn system for multi parametric wireless monitoring using GSM network is presented [83].

3.2 Health monitoring using wireless LANs

The monitoring of patients in a hospital or nursing home can be performed by using infrastructure-oriented wireless networks such as wireless LANs [26]. This will allow monitoring for mobile and stationary patients in indoor and outdoor environments (Fig. 4). Due to its availability, 802.11 WLANs are being used in healthcare systems such as ECG monitoring systems [77] and in some cases, in conjunction with Bluetooth technologies [78]. Also, WLANs have been used and evaluated for continuous monitoring during intra-hospital transfer [82]. There are several issues related to monitoring using WLANs including service area and signal reception, throughput and bit rates, number of patients that can be supported, signal transmission from patients to access points, location accuracy, protocol, and reliability of monitoring [52].

The service area of most access points in WLANs is affected by mobility, obstacles, frequency, and the medium the signal must pass through between access points and the patients. To increase the coverage of a wireless LAN, the number of access points can be increased, resulting in a higher initial cost. Also, the availability of wireless links between patients and access points is dependent upon the power level and interference. The throughput, or actual number of bits that can be transmitted after subtracting overhead and retransmission, decreases with an increasing distance between patients and access points, so either a higher number of access points per wireless LAN or a higher bit rate wireless LAN should be considered. The number of patients that can be supported by an access point will depend on the bit rate, frequency of monitoring, and the amount of information per patient per monitoring event.

In WLANs, monitoring delays could occur as patient's device will have to wait before transmission. As WLANs are designed for data-type traffic where delays are not critical, however, such problems will affect the quality of health monitoring. The monitoring delays could rise substantially, if more patients are in the coverage of the same access point due to locational restrictions or due to mobility.

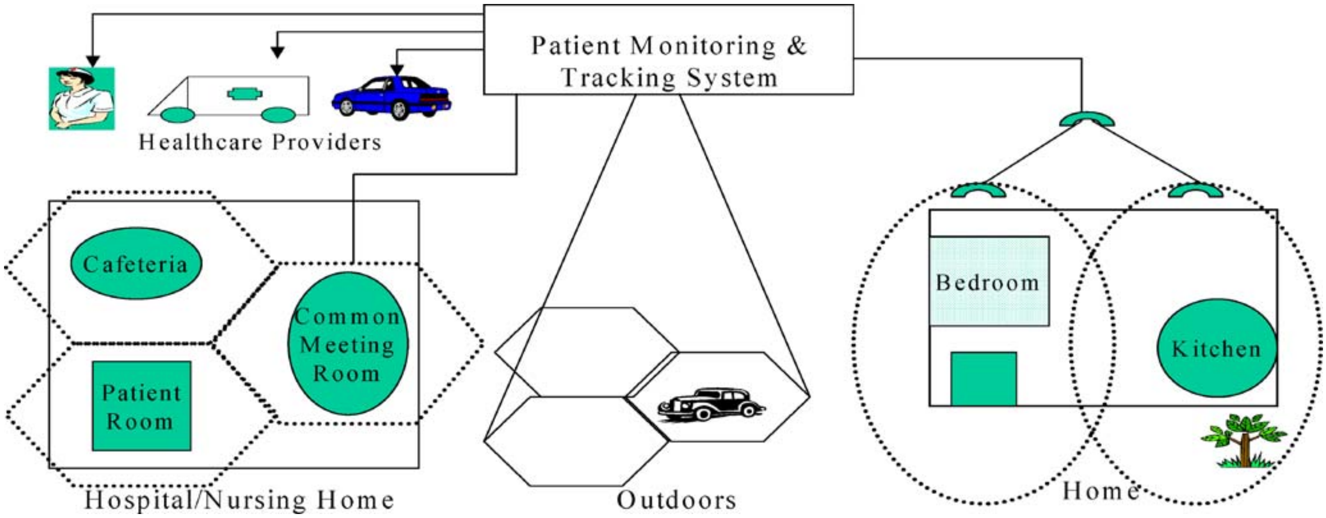


Figure 4 Health monitoring using wireless LANs

In some cases, the delays can be reduced using prioritized transmission.

The mobility of patients will create uneven number of users under different access points. This will affect both throughput and delays for health monitoring. Health monitoring does require location management of patient and to support this, individual access points can maintain a list of currently supported patients. This would lead to location management with an accuracy equal to the coverage of the access point. For an increased level of accuracy, access points can combine other location management technologies such as RFID (radio frequency identification).

The major issue is the reliability of health monitoring using WLANs, which will be affected by coverage and signal strength, available bit rate and prioritized transmission, delay performance, and failure of access points and interconnection architecture. To reduce the impact of access point failures, both overlapping and backup access points could be deployed. The access points can be interconnected in a grid of wireless LANs using mesh-based interconnection. The mesh, due to its rich interconnection pattern or high redundancy of links, is a highly reliable interconnection architecture.

The protocol for health monitoring using WLANs should involve the following steps:

1. Patient's devices to locate and join an access point
2. Patient's device to measure vital signs (if above or below normal, transmit a signal to access point using higher priority. If matches a pattern or highly above or below normal, transmit an "emergency" signal to the access point using highest priority)
3. Access point to route the message to one or more healthcare providers along with past vital signs (from a database) and the current location of the patient.

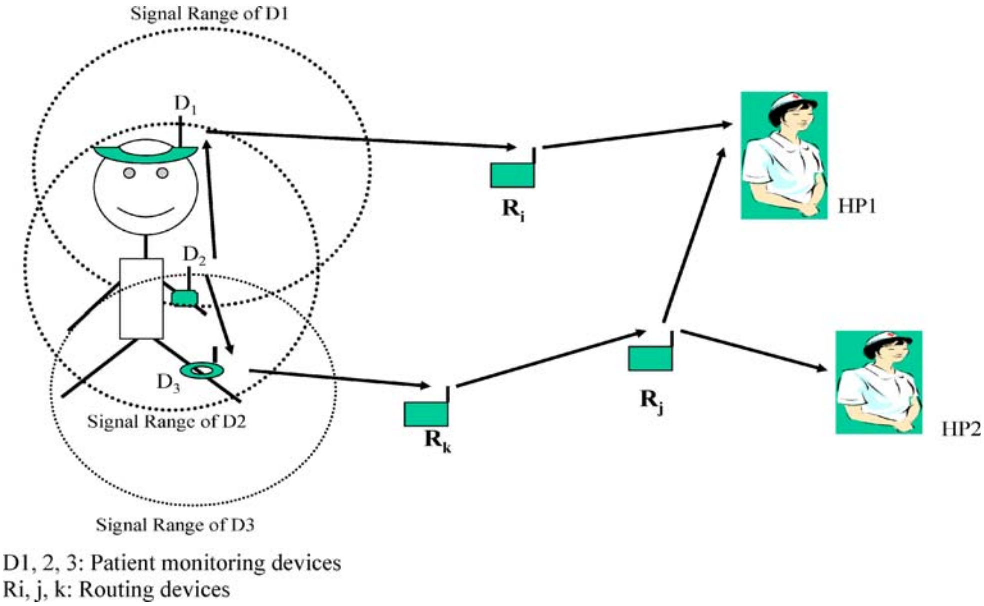
Also, the number of patients that can be monitored under every access point can be limited to provide both improved and reliable health monitoring services. These limits can be derived for multiple versions of 802.11 WLANs, based on the traffic generated (frequency of monitoring and packets per monitoring event) and the delay requirements. More work can also be done in modifying WLAN protocols to suit healthcare applications. This could include support for priority for healthcare data, improved security and privacy, higher bit rates, and, support for both continuous and infrequent (as needed) monitoring.

3.3 Health monitoring using Ad Hoc wireless networks

The potentially spotty coverage of existing infrastructure-oriented wireless networks will significantly affect the delivery of monitoring messages [46, 52]. These could result in many cases and scenarios where continuous health monitoring is not possible and/or emergency signals may not be transmitted from a patient to healthcare providers. For these situations, health monitoring can be achieved by using ad hoc wireless networks [37], formed among patients' devices that can transmit vital signs over a short range (Fig. 5). The information on vital signs of a patient can be transmitted to another nearby patient and so on, thus increasing the chance that vital signs are picked up by a healthcare professional on his/her device.

There are many challenges in ad hoc wireless networks for health monitoring, including routing of monitoring messages with changes in network connectivity and user locations. Several routing schemes, which differ in how messages are routed to a destination, can be considered. Each of these schemes brings its own complexity, overhead and performance in terms of reliability of message delivery and end-to-end delays. The impact of patient mobility,

Figure 5 Ad Hoc networks in wireless patient monitoring



limited device range and failures of routing devices is also likely to be very different on the reliability of these routing schemes. For example, unicast routing will have the worst performance if an intermediate device has failed, moved or is simply not cooperative. While multicast and broadcast routing could lead to much higher reliability of message delivery, the amount of network traffic and monitoring delays could be high. It may be possible to switch between the types of routing to allow multiple levels of required performance for messages carrying vital signs of different levels of emergencies.

There are additional challenges that must be addressed in transmission of emergency signals over ad hoc wireless networks. These challenges include power management, reliable transmission, and cooperation of other devices. Power management has been an important issue in ad hoc networks, however, in health monitoring, it becomes even more important as the transmitted power can influence both the ability of a patient device to transmit monitoring signals as well as the end-to-end routing of these signals [60]. Also, if a patient's device has been involved in the routing of many prior messages from other patients, it may not have sufficient power left when it needs to transmit its own signals. Therefore, power conservation is necessary for such devices, and can be realized by minimizing the frequency and the number of vital signs. Also, the vital signs can be coded differentially to reduce the number of bits that are generated and transmitted in a message.

Possible enhancements for improving the delivery of monitoring messages include (1) increased power transmission for improving the chances of finding cooperating devices or a healthcare professional, (2) multiple retransmissions and hop-by-hop acknowledgements, (3) increasing the number of cooperating devices (including fixed devices) and healthcare professionals, (4) transmission of differential value of vital signs, and, (5) use of multiple ad hoc networks [60]. The cooperation of other devices for helping in the routing of monitoring messages in one or more ad hoc networks can be achieved by offering incentives for routing. These could include certain credits for routing which can be used for reducing nursing home expenses, for membership in ad hoc networks when needed, and for prioritized routing of their messages. In some cases, the cooperation of other devices can be made as a requirement for a patient to be in a nursing home or hospital [54].

From an implementation point of view, existing wireless networks such as Bluetooth and 802.11 in ad hoc mode could be considered. Even as an example of simple implementation without priority, there are some problems that must be addressed: the range and achievable bit rates of ad hoc networks, a lack of a dynamic priority-based multi-hop routing protocol, a lack of cross layer communication for routing messages based on contents, a lack of dynamic adaptation of physical power for maximizing range under emergency conditions, and difficulty in deciding and dynamically switching to a different routing protocols. The range of existing wireless ad hoc networks (8021.11) is less than hundred meters and is about 10 meters for Bluetooth. The bit rates offered are likely to be in few hundred Kbps to tens of Mbps. Both range and bit rates could be adequate for health monitoring applications, if the frequency of monitoring is low with a few patients. For use of Bluetooth as an ad hoc network for health monitoring, the number of users (patients) per piconet is also limited to 8. This will affect the total number of patients that can be monitored. If multiple piconets are used, then interference in ISM band may limit the number of types of vital signs that can be transmitted for monitored patients. Also, Bluetooth enforces power control by dividing users among three types, which could affect the range of monitoring.

The existing ad hoc networks do not use sophisticated multi-hop routing protocols that are necessary to support health monitoring services. Also, cross-layer communication, intelligent power control and management for improved transmission of emergency signals based on the contents of messages must be added. In addition, there are many challenges, which may also limit the use of existing ad hoc networks for health monitoring, such as possible crowding of ISM bands by the presence of other wireless LANs, interference from medical and other devices generating signals in ISM bands, and the usable capacity of ISM bands for transmitting a large number of vital signs for many patients frequently. The availability of a wider dedicated band will significantly improve the quality of health monitoring services for patients.

4 Context awareness and reliability

Comprehensive health monitoring should be autonomous, context aware and reliable, however these challenges have not been addressed in health monitoring research. Certainly more work is needed before comprehensive wireless health monitoring will become a reality. In general, several unique attributes of comprehensive wireless health monitoring are:

- The use of personalized and multi-threshold health monitoring
- Autonomous and context aware monitoring
- Improvement in the correctness of medical decision making by utilizing a range of information along with context awareness
- Adaptive health monitoring to balance patients requirements' and network traffic
- Multi-point enhancements, including monitoring devices, networks, and healthcare professional devices, to improve the end-to-end reliability
- The improved infrastructure scalability by utilizing traffic management techniques, such as use of live and stored health information and context aware priority

The comprehensive health monitoring could cover scenarios involving patients with different levels of mobility, locations, timeliness of monitoring, and, reactive vs proactive monitoring. In passive monitoring, the vital signs are recorded for a subsequent analysis by healthcare professionals, while active monitoring involves generation, transmission and analysis of live vital signs and related information. These can be further divided in continuous or event-driven, based on whether the monitoring is continuous or event-driven such as passage of time or patient intervention. The health monitoring can also focus on stationary or mobile patients. For health monitoring, a patient could wear a wearable computing system such as Smart Shirt [57] or its LifeShirt version [58], or use a handheld device with sensors. The most demanding is the active continuous monitoring involving mobile patients wearing monitoring devices and needing pervasive coverage without their intervention or inputs [84].

These variations of health monitoring defers in their quality of service requirements. Since such requirements do not exist formally yet, we define several attributes, termed Healthcare Quality of Service (H-QoS), as follows.

1. *Patient-centric H-QoS* are reliability of message delivery and monitoring delay.
2. *Network-centric H-QoS* are message throughput and number of patients supported.
3. *Healthcare professional-centric H-QoS* are cognitive load of healthcare professionals and the number of correct medical decisions.

4.1 Context aware health monitoring

Context is any information that can be used to characterize the situation of an entity, which is a person, place, or object that is considered relevant to the interaction between a user and an application, including the user and applications themselves [61]. Context can consist of both implicit and explicit information and can even be further divided among low level (such as time, temperature, and bandwidth) and high-level contexts (complex user activity) [62]. The primary context types are location, identity, time, and activity [61]. In healthcare environment, the context types may also include current medications, handicaps, and current environment and may relate with a person's identity and/or location, but likely to change with time. In wireless health monitoring, healthcare professionals will make decisions based on knowledge derived from multiple set of informational items such as patient's medical history, current vital signs, medical knowledge, and specific patient conditions. Figure 6 shows how medical information can be represented for individual patients to achieve a high degree of personalization. The vital signs are defined with multiple thresholds, set of actions, undesirable patterns, and inter-relationship between multiple vital signs. The representation of medical information will be helpful for designing a comprehensive health monitoring system by utilizing both stored and live information. This along with the patient's current context (surroundings, patient's current activity, and emotional/physical states) will lead to a more suitable action by healthcare professionals.

A system is considered context aware if it uses context to provide relevant information and/or services to the user, where relevancy depends on the user's task [61]. This could

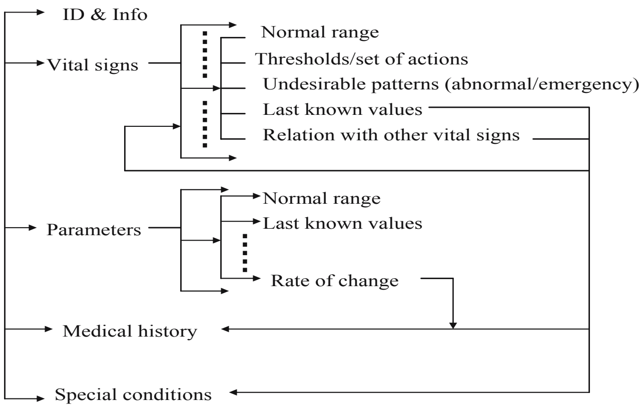


Figure 6 Representation of patient information

include both "passive" context awareness where the system become aware of, but does not adapt to the changing contexts, and "active" context awareness, where the system adapts to the changing contexts. Comprehensive wireless health monitoring system should be actively context aware, which will also aid in a better decision making by healthcare professionals on patient's current conditions and healthcare needs. In health monitoring, users can be patients whose primary task is being monitored for one or more health conditions and receive necessary medical attention, or healthcare professionals, whose primary task is to receive current and accurate information on monitored patients and perform decision making on patients' conditions and required care.

One vital sign is represented as an ECG signal with multiple waves, which follows a certain pattern with duration (pulse rate) and intensity. Any significant changes in wave pattern may indicate patient-specific cardiovascular problems. For example, relative variations in different waves in ECG indicates a range of health problems such as missing or weaker P wave indicates atrial problems affecting blood flow to the heart. A large increase in Q wave with respect to overall QRS indicates myocardial infraction (heart attack), while inverted T wave indicates ischemia. In addition to the current values of vital signs and patient-specific thresholds, the health monitoring system, to differentiate a multitude of situations, could also utilize physical location, physiological and emotional states, personal health history, and, current activities. In addition, in case of the availability of sensors, such information could also be utilized with patient's history of medical information. In essence, the health monitoring can lead to identification of physical health, behavioral health and emotional health [65]. The context-aware protocols will be utilized to derive the current context of patient's healthcare needs and the quality of service requirements for transmission of vital signs (Fig. 7; [84]). More specifically, context-awareness can be utilized to derive the QoS requirements by differentiating among the multiple possibilities represented by absolute values of vital signs and thresholds [84]. Thus context-awareness can lead to a better derivation of the level of emergency for a monitored patient. The information on missing doses, recent labs, known handicaps, and unusual conditions will also be very useful in health monitoring.

The context generated will then be transmitted over networks along with live patient information. In some cases, based on the current status and the level and type of disability, a patient could correct the "derived" context, which will improve the accuracy of health monitoring, however, this is not a requirement as the system is designed to operate in an autonomous environment. The context-generation protocols are designed to *assist* and not *replace* the medical decision making by healthcare professionals. The protocols can be stored and processed in the health monitoring devices that a patient can carry or wear as a part of smart clothing. The context-generation protocols can be modified to work with incomplete and/or missing information in deriving the patient's context and healthcare needs.

For fulfilling the vision of context awareness in wireless health monitoring, more work is needed in designing and implementing context-aware protocols and performance evaluation of health monitoring system. As shown in the early work of context awareness in electronic patient records, [63] there is a promise for improved healthcare delivery but challenges including considerable complexity and training of healthcare professionals for context-aware applications must be addressed. A reduced complexity in context awareness can be ensured by having only a finite number of allowable contexts [66]. Preliminary work on context awareness in a hospital setting by context aware hospital bed and pill container, which can also adapt to changing context, shows how future research in context-aware medical system can be performed [64]. The future

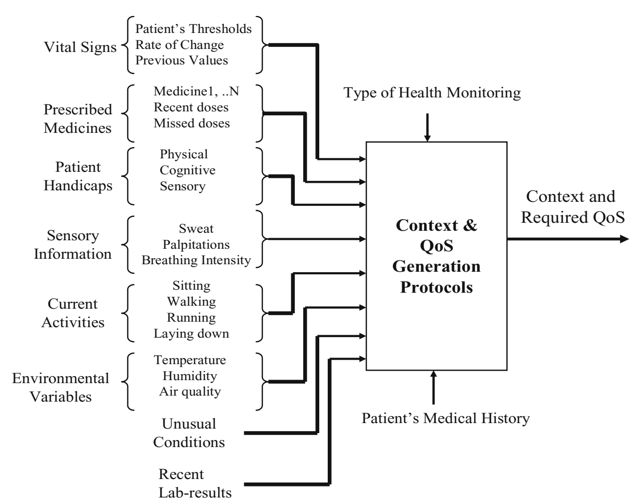


Figure 7 Patient's healthcare context and QoS requirement

research must also address systems that are not only passively context aware, but can actively adapt to context changes by modifying services to patients and healthcare professionals. This could lead to scenarios where trade-off between the quality of wireless health monitoring and the level of complexity due to context awareness must have to be considered.

4.2 Reliable health monitoring

4.2.1 Infrastructure reliability

Comprehensive wireless health monitoring requires a highly reliable network access anywhere anytime. One way to create reliable access is to utilize multiple wireless networks that may be available at a given location. The vital signs and environmental variables can be divided in several packets, transmitted over networks, and aggregated before being delivered to one or more healthcare professionals, who could also access/receive stored information on the patient. This reliable wireless network architecture will allow health monitoring to work even under:

- *Failure in networks:* when base stations, mobile devices, or databases experience failure
- *Coverage limitations:* when cellular wireless networks experience coverage problems
- *Intermittent access:* when a device is unable to access a network continuously

The reliable wireless network architecture will allow users to overcome time and/or location-sensitive disconnectivity or intermittent connectivity problems and failures in one network by switching to another wireless network. We assume (a) devices have the intelligence to sense presence of multiple wireless networks, (b) local characteristics of individual wireless networks are available and can be used in deciding which network to switch to, and, (c) devices have the hardware to switch among multiple networks. A possible architecture is shown in Fig. 8, where health monitoring devices can access and switch among cellular/3rd Generation, wireless LANs, ad hoc wireless networks, and sensors-based networks. Each of the networks may have its own complexity in terms of total bandwidth, usable bandwidth, coverage and reliability, required power level for transmission, priorities for access and transmission, and, any protocol specific requirements. For example, satellites may have wider outdoor coverage; however the indoor coverage is not reliable. Wireless LANs can offer inexpensive network access in Industrial, Medical and Scientific (ISM) band, which is also unlicensed for lots of other use. Cellular/PCS/GSM networks offer high quality access, but the cost for access may be too high for continuous health monitoring. Also, the location and time-dependent dead spots may affect the quality of comprehensive health monitoring. Sensors and RFID are very short range and will be needed in large numbers to provide any reasonable coverage. Although individually a single wireless network may not be able to provide reliability, coverage, and networking resource necessary to allow highly reliable health monitoring, but the ability to access and switch among multiple networks may create a fault-tolerant architecture with richer set of resources, capable of overcoming multiple problems. In the next few years, Fourth Generation (4G) wireless networks could emerge allowing users to access multiple wireless

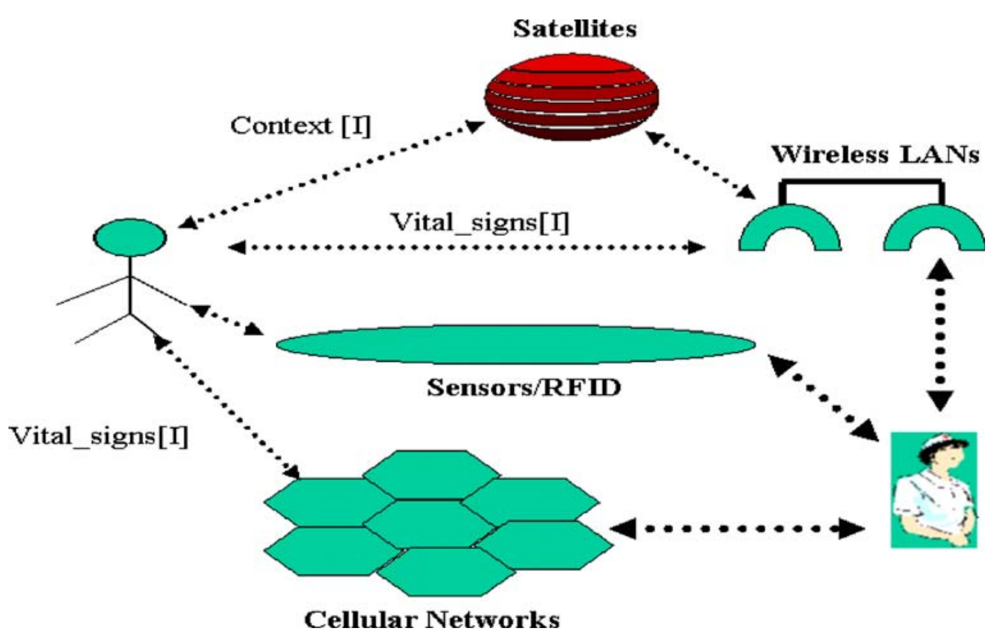


Figure 8 Reliable health monitoring with multiple wireless networks

networks without manually switching from network to network. Additional research is needed in estimating the overhead of multi-network access including handoffs among networks, processing overhead of dividing and aggregating vital signs and related information, and the level of end-to-end reliability achieved in several different variations of the architecture.

4.2.2 Reliability of health monitoring and message delivery

One of the most difficult challenges in health monitoring using wireless networks, especially for emergency messages, is the reliability of message delivery. Many hospitals and nursing homes are deploying infrastructure-oriented wireless networks, such as wireless LANs, satellites, and cellular and GSM (Global System for Mobile communications) systems, where a fixed infrastructure is utilized to support fixed and mobile patients. The unpredictable quality and reliability could lead to difficulty in achieving continuous health monitoring and delivery of monitoring signals from a patient to healthcare professionals, and eventually, the delayed medical response to patients could result in injury. To support the reliability and monitoring delay requirements of health monitoring, a significant work is necessary in creating wireless network architecture and protocols to support routing and delivery of messages carrying a range of vital signs and healthcare information. To improve the reliability of wireless health monitoring, one or more of the following enhancements can be considered: (a) use of multipath routing such as multicast or broadcast, (b) increased power transmission, (c) design of network or middleware protocols for end-to-end reliability [60].

5 Open issues and challenges

There are many open issues and challenges in realizing the vision of pervasive healthcare. These include a lack of comprehensive coverage of wireless and mobile networks, reliability of wireless infrastructure, general limitations of handheld devices, medical usability of sensors and mobile devices, interference with other medical devices, privacy and security [20, 21], payment and many management issues in pervasive healthcare.

The technology issues related to pervasive healthcare includes networking support such as location tracking, routing, scalable architectures, dependability [25], quality of access, how to provide health monitoring in diverse environments (indoor, outdoor, hospitals, nursing homes, assisted living), continuous vs event-driven monitoring of patients, use of mobile devices for healthcare information storage, update, and transmission, sensing of vital signs and transmission using cellular networks and wireless LANs, formation of ad hoc wireless networks for enhanced monitoring of patients, managing healthcare emergency vehicles and routing and network support for mobile telemedicine. The design and development of comprehensive wireless health monitoring system should address one or more challenges identified in this paper, namely context awareness, autonomous and adaptive behavior, and reliability of wireless health monitoring.

The medical aspects are very important in realizing a wide-scale deployment of wireless in healthcare. The issues of how patient care is delivered, how medical information can be represented, and requirements of diverse patients must be addressed. Many important issues are design of suitable healthcare applications, specific requirements of vital signs in healthcare environment, the diversity of patients and their specific requirements, representation of medical information in pervasive healthcare environment (multimedia, resolution, processing and storage requirements), role of medical protocols, improved delivery of healthcare services, and the usability of wireless-based solutions in healthcare. The requirements presented vary significantly from keeping track of the behavior of kids to how to avoid wandering and getting lost for dementia patients. It will be a major challenge to involve people with mental illness to use wireless infrastructure due to limited functional intelligence or very limited memory (such as those suffering from dementia). Many patients with paranoia may develop a suspicion towards wireless technologies, especially those once requiring a patient to wear a locator or other device.

The management of pervasive healthcare could bring a mini-revolution in terms of how wireless in the healthcare is implemented, offered and managed. There are many challenging and diverse management issues that must be addressed including the security and privacy in wireless healthcare, training of healthcare professional for pervasive healthcare, managing the integration of wireless solutions, increasing coverage of healthcare services using wireless technologies, legal and regulatory issues, insurance payments and cost aspects, and the potential implications of HIPAA (Health Insurance Portability and Accountability Act of 1996). The usability and integration of wireless-based solutions in healthcare is another challenge. The devices must be designed to offer intuitive interfaces that can learn with and from individuals. It has been shown that many less-technical-savvy population segments are willing to learn and use mobile and wireless technologies for allowing them to live more independently. The training of healthcare professionals to effectively utilize mobile and wireless technologies would be a less complex issue as an increasing number of those are using handheld and wireless devices. Another major issue is how to reduce the cost of delivering healthcare services to as many people by using wireless infrastructure. Other challenges in the large-scale introduction of wireless infrastructure in healthcare are legal and regulatory such as the issues of liability and lawsuits in USA and possibility of insurance companies not paying or paying differently for treatment via mobile devices. Another major issue is privacy and possible misuse of patient medical information. In U.S., a major regulation termed HIPAA (Health Insurance Portability and Accountability Act of 1996) designed for protecting such information has received some controversy and has been interpreted differently by major players, healthcare providers, insurance and attorneys. Therefore, work is needed in addressing privacy and related concerns over wireless and mobile networks where security is still seen as insufficient.

6 Conclusions

The role of wireless infrastructure in healthcare application is expected to become more prominent with an increasingly mobile society and the deployment of mobile and wireless networks. In this paper, we presented pervasive healthcare, wireless networking solutions and several important and interesting research problems. The pervasive healthcare applications include pervasive health monitoring, intelligent emergency management system, pervasive healthcare data access, and ubiquitous mobile telemedicine. The wireless networking solutions included use of wireless LANs, ad hoc wireless networks, cellular/GSM/3G infrastructure-oriented networks and satellite-based systems. We discussed in depth many challenges related to comprehensive wireless health monitoring system. More specifically, we discussed context awareness, reliability, and, autonomous and adaptiveness of wireless health monitoring system and presented high-level solutions which can be expanded in future research. It is expected that several challenges identified in this paper will be addresses by others researchers and developers and we will reach a step closer to realizing the vision of pervasive healthcare.

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Upkar Varshney is an Associate Professor of Computer Information Systems at Georgia State University. His current interests include ubiquitous and pervasive computing, wireless networks, pervasive healthcare, and mobile commerce. He is the co-founder (with Prof. Imrich Chlamtac) of International Pervasive Health Conference (http://www.pervasive-health.org) and co-chaired it in 2006. Upkar is also the program co-chair for Americas Conference on Information Systems (AMCIS-2009). He authored over 120 papers including more than 40 in refereed journals. Several of his papers are among the highly cited papers in wireless and mobile commerce and according to Google-Scholar, the total number of citations for his papers exceeds one thousand. Upkar has presented over 50 tutorials, workshops, and a few keynotes at major wireless, computing, and information systems conferences. He has also received grants from several funding agencies including the prestigious National Science Foundation. His teaching awards include Myron T. Greene Outstanding Teaching Award (2004), RCB College Distinguished Teaching Award (2002), and Myron T. Greene Outstanding Teaching Award (2000). He has served or is serving as an editor/ guest editor for several journals including IEEE Transactions on IT in Biomedicine, ACM/Springer Mobile Networks (MONET), IEEE Computer, Decision Support Systems (DSS), Communications of the AIS (CAIS), Int. J. on Network Management (IJNM), Int. Journal on Mobile Communications (IJMC).