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Wireless sensor networks for healthcare: A survey

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ABSTRACT

Becoming mature enough to be used for improving the quality of life, wireless sensor network technologies are considered as one of the key research areas in computer science and healthcare application industries. The pervasive healthcare systems provide rich contextual information and alerting mechanisms against odd conditions with continuous monitoring. This minimizes the need for caregivers and helps the chronically ill and elderly to survive an independent life, besides provides quality care for the babies and little children whose both parents have to work. Although having significant benefits, the area has still major challenges which are investigated in this paper. We provide several state of the art examples together with the design considerations like unobtrusiveness, scalability, energy efficiency, security and also provide a comprehensive analysis of the benefits and challenges of these systems.

1. Introduction

Wireless sensor network technologies have the potential to change the way of living with many applications in entertainment, travel, retail, industry, medicine, care of the dependent people, and emergency management and many other areas. Wireless sensors and sensor networks, pervasive computing, and artificial intelligence research together have built the interdisciplinary concept of ambient intelligence (AmI) in order to overcome the challenges we face in everyday life [1]. One of the major challenges of the world for the last decades has been the continuous elderly population increase in the developed countries. Population Reference Bureau [2] forecasts that in the next 20 years, the 65-and-over population in the developed countries will be nearly 20% of the overall population. Hence the need of delivering quality care to a rapidly growing population of elderly while reducing the healthcare costs is an important issue. One promising application in that area is the integration of sensing and consumer electronics technologies which would allow people to be constantly monitored [3]. In-home pervasive networks may assist residents and their caregivers by providing continuous medical monitoring, memory enhancement, control of home appliances, medical data access, and emergency communication [4,5]. Constant monitoring will increase early detection of emergency conditions and diseases for at risk patients and also provide wide range of healthcare services for people with various degrees of cognitive and physical disabilities [6]. Not only the elderly and chronically ill but also the families in which both parents have to work will derive benefit from these systems for delivering high-quality care services for their babies and little children.

Researchers in computer, networking, and medical fields are working together in order to make the broad vision of smart healthcare possible. The importance of integrating large-scale wireless telecommunication technologies such as 3G, Wi-Fi Mesh, and WiMAX, with telemedicine has already been addressed by some researchers. Further improvements will be achieved by the coexistence of small-scale personal area technologies like radio frequency identification (RFID), Bluetooth,

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ZigBee, and wireless sensor networks, together with large-scale wireless networks to provide context-aware applications [7]. Besides providing pervasiveness with existing and relatively more mature wireless network technologies, the development of unobtrusive small sensor devices enabling not only accurate information but also reliable data delivery is of great importance. Moreover, the glue combining all these technologies is the application, which is the coordinator between the caregivers and the caretakers and between the sensor devices and all of the actors in the overall system cycle. Since the application is the core of the high-quality healthcare service concept, the need for intelligent, context-aware healthcare applications will be increased.

Given the importance of the subject, there are already several applications and prototypes on the subject. For example, some of them are devoted to continuous monitoring for cognitive disorders like Alzheimer's, Parkinson's or similar cognitive diseases. Some focus on fall detection, posture detection and location tracking and others make use of biological and environmental sensors to identify patients' health status. There is also significant research effort in developing tiny wireless sensor devices, preferably integrated into fabric or other substances and be implanted in human body.

There are other survey studies in the literature [8–12]. However, these studies have either only smart home perspective or limited information about the design issues and challenges. In this survey, we evaluate the state of the art research activities and present issues that need to be addressed to enhance the quality of life for the elderly, children and chronically ill people. We provide survey of the recent research on future intelligent monitoring applications not only from a smart home perspective but rather from a more healthcare related perspective. We also discuss benefits that will be achieved and challenges that will be faced while designing the future healthcare applications.

The rest of this paper is organized as follows: Section 2 gives an overview of the design issues for healthcare monitoring systems using wireless sensor networks (WSNs) and discusses benefits of these systems. Section 3 describes several applications and prototypes. Section 4 discusses challenges of healthcare monitoring solutions using WSNs and addresses open research problems on the subject. Finally, Section 5 concludes the paper.

2. Benefits and design considerations for healthcare monitoring systems

The medical applications of wireless sensor networks aim to improve the existing healthcare and monitoring services especially for the elderly, children and chronically ill. There are several benefits achieved with these systems. To begin with, remote monitoring capability is the main benefit of pervasive healthcare systems. With remote monitoring, the identification of emergency conditions for at risk patients will become easy and the people with different degrees of cognitive and physical disabilities will be enabled to have a more independent and easy life. The little children and babies will also be cared for in a more secure way while their parents are away. The special caregivers dependability will be decreased.

In healthcare applications, a real-time system is actually a soft real-time system, in which some latency is allowed [13]. Identifying emergency situations like heart attacks or sudden falls in a few seconds or even minutes will suffice for saving lives considering that, without them these conditions will not be identified at all. Therefore, providing real-time identification and action taking in pervasive healthcare systems are among the main benefits.

The technology advancements in consumer electronics have reduced the production costs and have made it possible to afford inexpensive sensor devices for ordinary users as well. Together with the mature and also inexpensive RFID technology, the costs for pervasive healthcare systems are within the affordable range for many people. In Caregiver's Assistant [14], inexpensive RFID tags are placed on household object and the systems precision can be increased at very low costs, by tagging more objects with these RFID tags.

Being able to identify the context is another benefit achieved with pervasive healthcare systems. Context-awareness enables us to understand the conditions of the people to be monitored constantly and environments in which these people are. This context information is achieved mostly by sensing systems that incorporate more than one type of sensing capabilities. By fusing the information gathered by several sensors, we may have a more clear understanding of the context. The context information helps better in identifying the unusual patterns and making more precise inferences about the situation. For instance, if we can identify the location of the person to be tracked and the activity he/she is busy with together with his/her vital signs; we can deduce useful information out of these. During night-time, being in the sleeping room in a lying position may not indicate something serious whereas lying down in the sleeping room in the middle of the day may indicate an alarm situation. Context-awareness provides this useful information to us.

There are several prototypes as well as commercially available products. When several applications are investigated, it is observed that these applications have common properties. Most of the existing solutions include one or more types of sensors carried by the patient, forming a Body Area Network (BAN), and one or more types of sensors deployed in the environment forming a Personal Area Network (PAN). These two are connected to a backbone network via a gateway node. At the application level, the healthcare professionals or other caregivers can monitor the vital health information of the patient in real-time via a graphical user interface (GUI). The emergency situations produce alerts by the application and these alerts and other health status information can be reached via mobile devices like laptop computers, Personal Digital Assistants (PDAs) and smart phones. The overview of a simple wireless sensor network application scenario is depicted in Fig. 1. Based on this observation, in a typical scenario, there are four different categories of actors other than the power users of the systems such as administrators and developers.

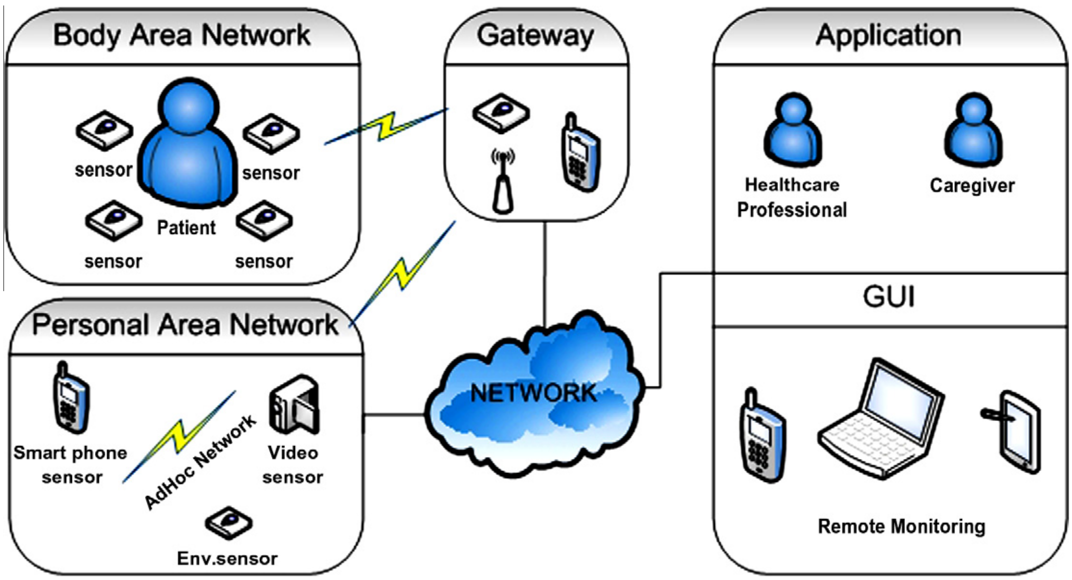

Fig. 1. Overview of a simple WSN application scenario for healthcare.

- Children: this group consists of young people who are not capable of taking care of themselves like babies, infants, toddlers or those who are more grown-up but still needed to be constantly monitored.
- Elderly and chronically ill: this group includes the chronically ill people who have cognitive difficulties or other medical disorders related with heart, respiration, etc. and the elderly people who also may have these symptoms, besides, who are more susceptible to sudden falls.

Table 1
The design considerations of pervasive healthcare monitoring systems.

Subsystem	Design consideration
Body Area Network Subsystem	Power consumption Transmission power Unobtrusiveness Portability Real-time availability Reliable communications Multi-hop routing Security
Personal Area Network Subsystem	Energy efficiency Scalability Self-organization between the nodes
Gateway to the Wide Area Networks	Security Congestion prevention
Wide Area Networks	Data rate Reliable communication protocols Secure data transmission Coverage
End-user healthcare monitoring application	Privacy Security Reliability User-friendliness Middleware design Scalability Interoperability Context-awareness

- Caregivers: this group is comprised of the parents and the baby-sitters of the children group and also the caregivers and other care network of the elderly and the chronically ill.
- Healthcare professionals: these are the professional caregivers like physicians and other medical staff who are responsible from the constant health status monitoring of the elderly and the chronically ill people and are capable of giving the immediate response in case of an emergency situation.

These groups of actors constantly interact with the wireless sensor network healthcare systems by using different subsystems. There are five subsystems in such a scenario: (i) Body Area Network Subsystem, (ii) Personal Area Network Subsystem, (iii) Gateway to the Wide Area Networks, (iv) Wide Area Networks, and (v) End-user healthcare monitoring application. In Table 1, the design considerations of these subsystems are provided.

2.1. Body Area Network Subsystem

The Body Area Network Subsystem is the ad hoc sensor network and tags that the children and the elderly carry on their body. The RFID tags, ElectroCardioGram (ECG) sensors, and accelerometers worn by the patient, are example components of the body area network. One of the main issues about the BAN is the power consumption, since changing the batteries is a burdensome task. Because of this, development of energy efficient Medium Access Control (MAC) protocols and energy efficient sensor devices are critical [15]. The study in [16] has shown that the technologies like Bluetooth and Wi-Fi fail to provide support for energy efficient systems since they can only offer one or two weeks runtime on a small energy source like a coin battery. The proper use of the wireless communication channels during routing ensures energy efficiency [17,18]. Moreover, by using very low power Pyroelectric Infra Red (PIR) sensors as in [19], a simple yet efficient remote monitoring application can be developed.

Another important issue is the output transmission power of the sensor nodes. The output power must be kept minimal for health issues which may lead to coverage and communication problems. The study presented in [20] investigates the bioeffects caused by radio frequency transmission of sensor nodes, including thermal and athermal effects and a control algorithm to reduce the bioeffects is proposed.

Unobtrusiveness must be a design consideration that cannot be overlooked. Yoo et al. [21] have designed an adhesive bandage type ECG sensor that is wirelessly powered by a health monitoring chest band. The sensors do not include batteries and wirelessly charged via the chest band instead. The network controller on the chest band is able to find the locations of sensors automatically and provide power only to selected sensors. The sensor IC is very small (4.8 mm area) and the network controller is also relatively small (15 mm area). They consume only 12 μW and 5.2 mW average powers, respectively, which makes them power-efficient devices. Barth et al. [22] designed a watch-shaped activity recorder which provides six-degrees-of-freedom inertial data. The device contains a 3-axes accelerometer and two gyroscopes and data transmission accomplished via Bluetooth. The system draws 185 mW in full operation mode that is, all sensors and the radio module are functioning.

Mobility and portability are other considerations for the physical design of such sensors, since the patients have to wear the BAN devices all the time and mobility reduction is not acceptable. The sensor devices must be designed with the aim of providing the highest degree of mobility for the patients [23], which necessitates the integration of several network technologies like RFID and Near Field Communication (NFC) as proposed in [24]. In [25], a smart shirt which measures ECG and acceleration signals continuously and transmits the physiological ECG data and physical activity data to IEEE 802.15.4 ad hoc network. The shirt consists of sensors for continuous monitoring the health data and conductive fabrics to get the body signal as electrodes. The study in [26] also makes use of ZigBee and mobile phone for ECG and blood glucose measurement. In a similar study [27], a sensor that can be integrated into clothing is designed to measure biochemical changes in sweat which may indicate some health related problems. The study has shown that the sensor has the potential to record real-time variations in sweat during exercise.

The real-time availability and reliable communications of the system is a further major issue since the data gathered by this system may be critical as in [28]. Nyan et al. have designed a wearable fall detection system that can detect the falls with an average lead-time of 700 ms before the incident occurs. Varshney [29] proposes a framework for high levels of reliability and low delays. The performance results show that reliable message delivery and low monitoring delays can be achieved by using multicast or broadcast-based routing schemes in an ad hoc network.

Additionally, designing multi-hop systems are of great importance. As in [30], continuous monitoring of the patient's ECG without range limit due to the extended communication coverage by multi-hop wireless connectivity, is one of the basic needs for such critical applications.

Finally, security issues also need to be considered since the physiological data of the individuals is highly confidential. In [31], the authors design a physiological signal based entity authentication scheme. The information extracted from physiological signals is used to generate identity information for mutual authentication. The proposed scheme allows the secure identity verification during wireless link setup process. In [32], a secure key establishment and authentication algorithm is used for transmitting medical data from body sensors like ECG sensors to a hand-held device of the mobile patient.

2.2. Personal Area Network Subsystem

This subsystem is composed of environmental sensors deployed around and mobile or nomadic devices that belong to the patient. The environmental sensors like RFID readers, video cameras, or sound, pressure, temperature, luminosity, and humidity sensors help providing rich contextual information about the people to be monitored. Location tracking can also be achieved by this subsystem. The smart appliances that are capable of communicating with other devices and taking actions can be included in the system.

In [33], a wireless "Personal Assistant" device that supports communications with three different medical devices, namely a glucometer, an insulin pump and a continuous glucose sensor, is presented. With the help of the patient's PDA device, medical devices can be controlled and context-awareness with a user-friendly interface is provided to the patient. Keeping the design modular, scalability, and allowing the easy integration of new functionalities are key issues here.

RFID tagged objects are also significant for this subsystem. They can convey detailed contextual information by mature and widely used RFID technology that can also support battery-free operation with the help of inexpensive tags. However, although a tag may be present, it may not necessarily be visible to the tag reader due to blocking by an impenetrable object [34]. Efficient algorithms for locating RFID tagged objects through appropriate data collection and preventing data interference are needed.

The energy efficiency of the MAC layer is another important issue. In [35], a MAC protocol is proposed which aims to improve energy efficiency by giving emphasis in the prevention of main energy consumption sources, such as collision, idle listening and power outspending. Also in [36] a variable control system is proposed to optimize the measurement resolution thus saving power. The higher resolutions of sensor devices will consume more energy. By using this system, the users can set the resolutions flexibly in any situation that they want to change the measurement resolution. In their experiments, the Signal-to-Noise Ratio (SNR) of ECG can be promoted from 25 to 73 dB when extraordinary ECG signal occurs.

The self-organization between the nodes is also essential. In miTag system [37], the data collected from a self-organizing wireless network of sensors that operate in mesh mode is relayed to the Internet. By making use of mesh mode operation and distributed processing, the system can be used during serious disaster conditions by deploying repeaters quickly and providing easily extendible coverage. In [38], a self-organizing distributed scheme is proposed for recognition of the activities of the people.

2.3. Gateway to the Wide Area Networks (WANs)

The gateway subsystem is responsible from connecting the BAN and PAN subsystems to the WANs. The gateway can be a mobile device carried by the user like a PDA or a smart phone, or a sensor node deployed in the environment as well as a laptop computer or a server computer. The main function of the gateway subsystem is to provide the connection between the ad hoc sensor networks to the infrastructure based WANs. Because of this property, the gateway subsystem can easily become the weakest link of the overall scenario. Therefore, local processing capability at the BAN and PAN subsystems, that has a great impact on the gateway subsystem, prevents network congestion by reducing the amount of the transferred data. The study in [39] focuses on this issue by collecting the ECG data coming from the sensor and processing the data on the cell phone locally before sending. In [40], context-awareness provides the capability of selecting the suitable network interface for the data transfer.

Security issues also need to be handled by the gateway subsystem. The security needs for this subsystem include verifying the correct identity of the source and not modifying the patient data, except for aggregation or other defined transformations [41]. The security scheme proposed in [42] employs a session key buffer to defeat gateway attacks. The delay between receiving the new session key and using it helps identifying the gateway compromise. The scheme also brings solutions to the man-in-the-middle attacks, session key and fake data injection. In Table 2, the summary of security requirements is given and possible solutions are provided.

2.4. Wide Area Networks for healthcare applications

For a remote monitoring and tracking scenario, a network infrastructure is inevitable. The gateway can relay information to one or more network systems depending on the application. The examples of network systems can vary from cellular networks to ordinary telephone network or from satellite networks to the Internet. These wide area networks have their own issues and properties independent of the healthcare application. While the data rate and reliable communication protocols for wide area networks advance, the ubiquitous healthcare applications will also benefit from it. The new and existing broadband networking technologies are needed to be integrated into the pervasive healthcare solutions in order to provide coverage up to global scale. In Table 3, the characteristics of the candidate wireless connectivity and mobile networking technologies are provided.

In order to extend the healthcare to a global scale, we may need satellite communication systems as well. Gabriel et al. [45] analyze satellite-based telemedicine networks, telemedicine applications and services. These projects mainly focus on improvement of the health care in remote locations, like marine vessels, or healthcare-deficient parts of the world that have no technological infrastructure. With the increased transmission capacity of the network, tele-consultation with remote experts will be possible. Likewise, satellites or High Altitude Platforms (HAPs) can provide healthcare services for disaster areas with quick and easy deployment.

2.5. End-user healthcare monitoring application

The application is at the heart of the system at which the collected data is interpreted and required actions are triggered. The application has a processing part and a graphical user interface part. The processing part performs the reasoning with some signal processing algorithms to understand a distorted cardiac signal for example, and with machine learning algorithms to identify an unexpected situation from an image or video. The graphical user interface is used for real-time monitoring of the vital sign information together with an alerting mechanism in case

Table 2
Wireless sensor networks security requirements and possible solutions [43].

Security threats	Security requirement	Possible security solutions
Unauthenticated or unauthorised access	Key establishment and trust setup	Random key distribution Public key cryptography
Message disclosure	Confidentiality and privacy	Link/network layer encryption Access control
Message modification	Integrity and authenticity	Keyed secure hash function Digital signature
Denial-of-service (DoS)	Availability	Intrusion detection Redundancy
Node capture and compromised node	Resilience to node compromise	Inconsistency detection and node revocation Tamper-proofing
Routing attacks	Secure routing	Secure routing protocols
Intrusion and high-level security attacks	Secure group management, intrusion detection, secure data aggregation	Secure group communication Intrusion detection

Table 3
Wireless connection technology candidates for pervasive health systems [44].

Technology	Candidate subsystem	Data rate	Cell radius	Frequency band
IEEE 802.11g/WiFi	BAN/PAN	54 Mbps	50–60 m	2.4 GHz
IEEE 802.11n/WiFi	BAN/PAN	540 Mbps	50–60 m	2.4 GHz
ETSI HiperLAN/2	BAN/PAN	54 Mbps	50–60 m	5 GHz
IEEE 802.16/WiMAX	WAN	36–135 Mbps for LOS, 75 Mbps for NLOS	Up to 70–80 km	2–66 GHz
IEEE 802.16e/WiMAX	WAN	30 Mbps	Up to 7080 km	2–6 GHz
ETSI HiperACCESS	WAN	25–100 Mbps	1.8–2.5 km	11–43.5 GHz
ETSI HiperMAN	WAN	25 Mbps	2–4 km	<11 GHz
WiBro	WAN	18 Mbps	1 km	2.3–2.4 GHz
High Altitude Platforms (HAP)	WAN	Varies	Varies	28–31 GHz and 42–43 GHz
IEEE 802.20	WAN	16 Mbps	>15 km	3.5 GHz
IEEE 802.22	WAN	18 Mbps	40 km	54–862 MHz
Satellite (GEO) Geostationary Earth Orbit	WAN	Up to a few Gbps	Four satellites give global coverage	4–8 GHz (C Band), 10–18 GHz (Ku), 18–31 GHz (Ka), 37–50 GHz (Q/V)
Satellite (MEO) Medium Earth Orbit	WAN	Up to a few Mbps	11 satellites give global coverage	Same as GEO
Satellite (LEO) Low Earth Orbit	WAN	Up to a few Mbps	Varies	Same as GEO

of an emergency. The application should also provide an interface for the definition and configuration of the system's overall behavior. What kind of alarms will be generated and via which network the messages will be delivered and who the intended users are examples of the application configuration. In such a system, most of the issues mentioned for other subsystems are also relevant along with the issues explained in the following sections.

2.5.1. Security

Security must be ensured throughout the healthcare application scenario. Therefore, end-to-end security mechanisms are needed. Based on the security requirements provided in Table 2, the patients' sensitive health information must be assured to be viewed by the authorized parties, the systems must be assured to be resistant against security attacks. The mostly studied security issues in the literature are related with encryption, generally. There are several proposals for key distribution protocols for encryption mechanisms [46,47]. Yet, before establishing encryption, the security policies must be addressed in the first place. Moreover, for multi-modal systems such as RFID enhanced pervasive healthcare systems, the security issues for every modality should be studied separately and there must be strong mechanisms against all kinds of attacks [48].

2.5.2. Privacy

Privacy is of most importance although in the study conducted with randomly selected seniors from several elderly community groups in Australia, the authors suggest that privacy of health information is not perceived as a highly significant concern and does not have a significant effect on an elderly person's perception or acceptance of WSN systems [49]. On the other hand, the same study reveals that, the seniors strongly reject being monitored by cameras. The users should have autonomy [50]. They must be enabled to have control over their information so that they can decide which information is transferred and during which intervals as in the CareNet display project [51]. In this way, the application must guarantee a well defined degree of privacy with precisely formulated and verified rules. In Smart Home Care Network [52], the use of image sensors is proposed only under emergency conditions and only for verification purposes. This scheme changes a probable privacy flaw into a privacy-respecting mechanism.

2.5.3. Reliability

The application should be reliable. In [53], the authors classify the issues of reliability into three main categories: reliable data measurement, reliable data communication, and reliable data analysis. Although the reliable data measurement and communication issues belong to the BAN and PAN subsystems, they are essential for the reliable data analysis at the application layer. They propose an architecture for handling data cleaning, data fusion, and context and knowledge generation for reliable data analysis. The data analysis is critical for pervasive healthcare systems since the inferences obtained from the data. Furthermore, the system should proved to be doing the job it was designed to accomplish. Faulty system components and exceptions must not result in system misbehavior.

2.5.4. Middleware design

The combination of sensors from different modalities and standards make it necessary to develop hardware independent software solutions for efficient application development [54,55]. In this context, there are numerous studies focusing on the middleware design [56–58]. Middleware helps to manage the inherent complexity and heterogeneity of medical sensor networks. The idea is to isolate common behavior that can be reused by several applications and to encapsulate it as system services. In this way, multiple sensors and applications can be supported easily; resource management and plug and play function becomes easy.

2.5.5. Context-awareness

Context-awareness, defined as "providing relevant information and/or services to the user, where relevancy depends on the user's task [59]", is the core issue for smart home applications as well as remote health monitoring applications [60]. Context-awareness can be provided

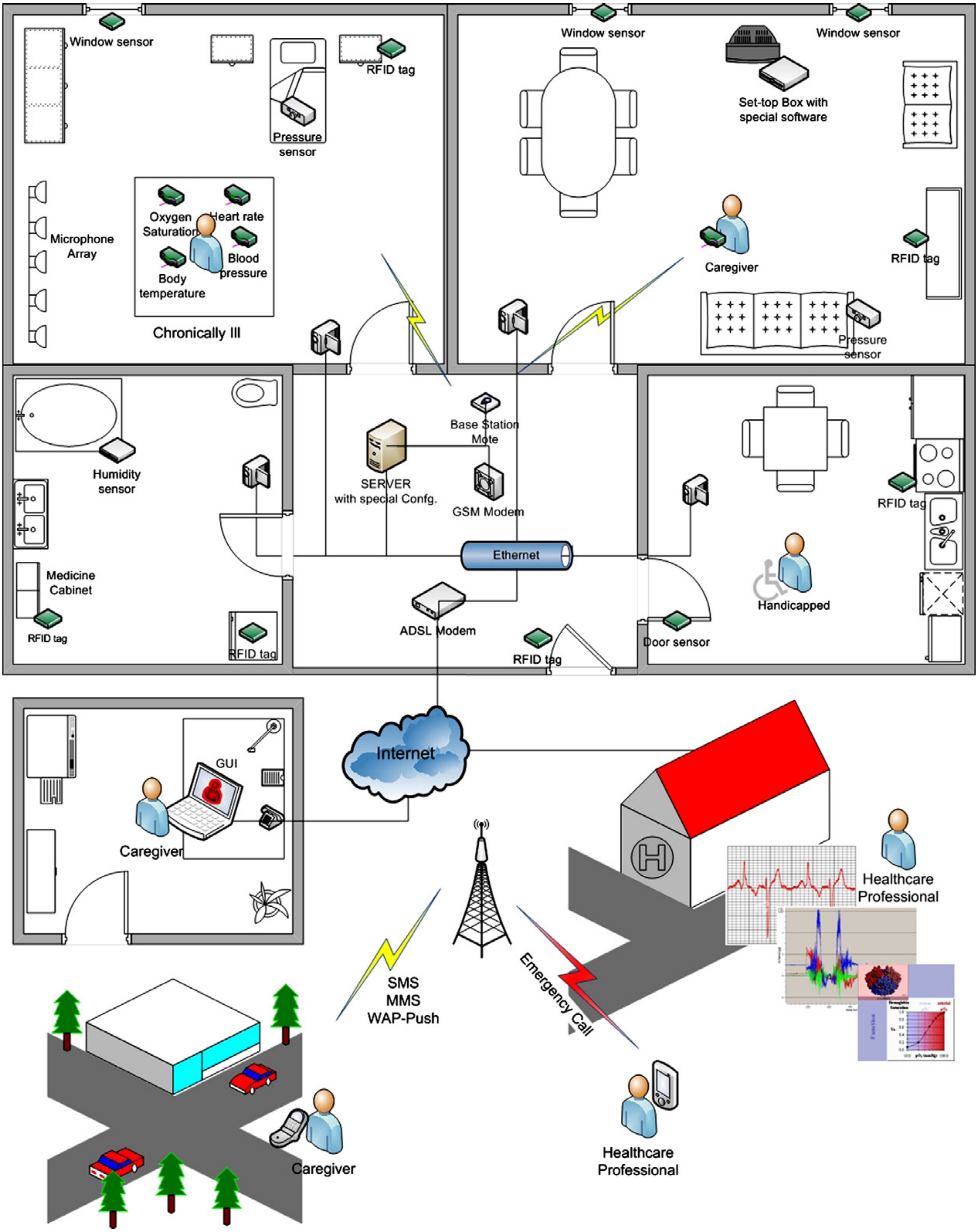

Fig. 2. A future scenario for a multi-modal seamless healthcare environment.

through the use of different sensing modalities together while considering previously mentioned issues such as proper data aggregation and analysis [61]. There are more ways for improving context information. In [62], a context model and context management framework is proposed. With the proposed ontology-based model, analyzing not only the rule-based alarm conditions but also more complex patterns becomes easier. This semantic representation of wireless sensor networks data enables structured information to be interpreted more clearly. Also in [63], a similar ontology-based context model is employed. The study in [64] defines a service-oriented ontology for wireless sensor networks. In a similar work [65], an ontology-based semantic collaboration mechanism is proposed. The system provides the cooperation among different persons in anytime, anywhere, and with anybody, thus reducing the complexity of making correct decisions and taking correct actions.

2.6. Seamless healthcare tracking and monitoring system

Based on the relevant work in the literature and taking the issues into consideration, a probable futuristic design of a multi-modal, seamless healthcare tracking and monitoring system can be seen in Fig. 2. In the figure, the chronically ill person in the bedroom carries a group of wireless sensors on his or her body constructing a BAN. These sensors constantly measure the vital signs of the patient and relay this data to the base station node connected to a specially configured home-server computer acting like a gateway between the BAN and the WANs like the Internet and the cellular or fixed telephony networks. The video and audio sensor nodes, RFID tags and other sensors like humidity, temperature, motion, etc. are emplaced in the living place and they are used to provide detailed context information about not only the patient but also the living place's conditions. These sensors form the PAN. In such a scenario, RFID tags can be used for location tracking, i.e. in which room the patients or the other residents are, with the help of small inexpensive RFID tags. In this way, when an emergency situation occurs, the location information helps to activate the closest video sensor node to obtain the best scene about the event. These video images can be delivered to the caregivers or healthcare professionals for further exploration via the Internet or cellular network through the gateway server. By using smart home appliances, the living place can be controlled or the interaction with the residents can be achieved. For example, if the patient is observed to be sitting on the coach in front of the television at medication time, then the smart set-top box can provide a reminder for the patient to take his or her medications. Another application example can be for the infants and babies. When the temperature of the room where the baby is sleeping may be below or above the optimal value, then the air conditioning device in the room can be automatically activated. When the baby is observed to be crying in his or her room and the caregiver is another room for some time, the speakers in the room can be activated to alert the caregiver. These scenarios are not very far from becoming ordinary for our lives with the development of seamless, pervasive healthcare systems.

3. Healthcare monitoring applications and wireless sensor network prototypes

There are several prototype and commercial applications for pervasive healthcare monitoring for the elderly, children and chronically ill people. When these applications are explored, it is observed that the main focus categories include (i) activities of daily living monitoring, (ii) fall and movement detection, (iii) location tracking, (iv) medication intake monitoring, and (v) medical status monitoring. In the first category, the applications try to identify and differentiate everyday activities of the patients and the elderly such as watching television, sleeping, ironing, and be able to detect odd conditions. Fall and movement detection applications are focused on the physiological conditions such as posture and fall detection for people that need special care like the elderly people who are susceptible to sudden falls which may lead to death, infants, or patients recovering from an operation. Location tracking and the medication intake reminder and monitoring systems can help cognitively impaired people to survive independently. Medical care applications make use of medical and environmental sensors in order to obtain comprehensive health status information of the patients, including ECG, heart rate, blood pressure, skin temperature, and oxygen saturation. In the following subsections we provide examples of applications belonging each category.

The research projects surveyed in this paper use different sensor types ranging from tiny biosensors to battery-free RFID tags. Some of the proposals deploy only a single type of sensors such as passive RFID tags or accelerometers while others deploy a combination of sensor types allowing multi-modal sensing. Most of the proposed works also present their special sensor hardware designs to provide specific measurements and interfaces to other devices. Likewise, nearly all of the projects have special software development; however, some of them have more structured and well-designed software systems together with appropriate API's and middleware. GUI design is also one of the key features of these applications, yet some of the projects do not have GUI integrated into the application. As far as the routing of critical information indicating health status of the patients is considered, there are very few applications that use multi-hop routing. Multi-hop routing is important in enlarging the coverage area of the application thus providing flexibility at the cost of complexity. Moreover, the level of being unobtrusive and context-aware differs among applications. Some of them use very tiny sensors integrated into clothing or video cameras that are not carried by the patient. These applications' obtrusiveness level is low. As the size and amount of the devices carried by the patients increase, this level goes up. Similarly, the context-awareness is at different levels among the applications. Some of them provide rich contextual information such as the time, location and status of different sensors, while others give only limited information about some specific event condition. In that sense, location tracking utility is important in providing detailed contextual information as well. When deducing meaningful information from sensor data, machine learning techniques are also important besides signal processing. Finally, some applications utilize inexpensive RFID tags to make location tracking and activity classification easier. The overall classification of the existing wireless sensor networks applications and related proposals are listed in Table 4. In the following subsections, one of the representative proposals is described in detail and important features of the others are given.

3.1. Activities of daily living monitoring applications

Lu and Fu [66] present an activity recognition approach with location-awareness. They use a variety of multi-modal and unobtrusive wireless sensors seamlessly integrated into ambient-intelligence compliant objects (AICOs), which are ordinary household objects overlaid by a virtual layer. The aim of the virtual layer is to capture interactions without interfering with natural manipulation of the object from residents. Based on the captured data, AICOs generate explicit and implicit features. These features are empowered by location information and fusion of them generates more reliable estimates. Also, the features are collected by ranking their usefulness in estimating activities of interest and their probability of failure. The ADL classification is accomplished by multiple naive Bayes classifiers, each of which represents an activity. This fact also enables identifying more than one activities that are done at the same time like listening to music while studying. Fig. 3 shows the hierarchical system architecture.

One of the key issues in this project is the design and development of the AICOs, since their objective is to collect the data naturally. Therefore, AICOs need to be integrated into objects in a way that do not change the previous interaction way of the residents with that object. For this reason, they prototyped a floor-AICO that contains one piezoelectric pad installed at the center of a mat with dimensions of approximately 30×30 cm. When these blocks are deployed on areas of interest, resident location identification can be achieved. Similarly, they also prototype a power-AICO that measures the power usage of electronic appliances, thus indicating the usage of that appliance such as television. Although deploying abundance of sensors in the living environment will increase the cost of this system, its reported performance is high when identifying activities like walking, listening to music, watching television, sitting and using microwave, especially with the addition of location assistance. In a similar study [91], the authors conduct experiments on 104 h of activity data collected from a person living in a home

Table 4
Pervasive healthcare monitoring applications overview.

		HW design	SW design	GUI design	Sensing modality	Hop Cnt	Obtrusive	Context aware	Mach. learn.	Loc. track.	RFID use
Activities daily living of (Section 3.1)	AICO [66]	Yes	Yes	Yes	Multi	Single	Low	High	Yes	Yes	Passive
	CareNet Disp. [51]	Yes	No	Yes	Multi	Single	Low	High	No	No	No
	Caregiver's Ast. [14]	No	Yes	Yes	Single	Single	Low	Medium	No	No	Passive
	WISP [67]	Yes	No	No	Single	Single	Low	Low	No	No	Passive
	LiveNet [68]	Yes	Yes	Yes	Multi	Single	High	High	Yes	IR tags	No
Fall and movement detection (Section 3.2)	ITALH [69]	Yes	No	Yes	Multi	Single	High	Medium	Yes	GPS	No
	Act. Mon.& Fall Det. [70]	No	No	No	Single	Single	High	Low	No	No	No
	Fall Detection [71]	No	No	No	Single	Single	Medium	Medium	Yes	No	No
	Smart Phone HCM[72]	Yes	No	Yes	Multi	Single	High	Medium	No	GPS	No
	Smart HCN [52]	Yes	No	No	Multi	Single	Medium	High	Yes	RSSI	No
	HipGuard [73]	Yes	No	No	Multi	Single	High	High	No	No	No
Location tracking (Section 3.3)	RFID way finding [74]	No	Yes	Yes	Single	Single	Medium	Medium	No	Yes	Passive
	Ultra Badge [75]	Yes	No	No	Single	Single	Low	Medium	No	Ultrasound	No
	ZUPS [76]	No	No	No	Multi	Multi	Low	Low	No	Ultrasound	No
	ALMAS [77]	No	No	Yes	Multi	Single	High	High	No	Yes	Active
	Passive mon. [78]	No	No	No	Multi	Single	Low	Low	No	RSS	No
Medication intake (Section 3.4)	RFID medic. ctrl. [79]	No	No	Yes	Single	Single	Low	Low	No	No	Active
	iCabiNET [80]	Yes	No	No	Single	Single	Low	Low	No	No	Passive
	iPackage [81]	Yes	Yes	Yes	Multi	Single	Low	High	No	No	Passive
Medical status monitoring (Section 3.5)	MobiHealth [82]	No	Yes	Yes	Multi	Single	Medium	Medium	No	No	No
	CodeBlue [83]	Yes	Yes	Yes	Multi	Multi	High	High	No	RF	No
	AlarmNet [84]	No	Yes	Yes	Multi	Multi	Medium	High	Yes	GPS	No
	LifeGuard [85]	Yes	No	Yes	Multi	Single	High	High	No	No	No
	Med. Supervision [86]	Yes	No	Yes	Multi	Multi	High	High	No	Yes	No
	FireLine [87]	Yes	No	Yes	Single	Single	Medium	Low	No	No	No
	Baby Glove [87]	No	No	No	Multi	Single	High	Low	No	No	No
	LISTENse [87]	Yes	No	Yes	Single	Single	High	High	No	No	No
	WLAN ECG [39]	Yes	No	Yes	Single	Single	High	Medium	No	No	No
	Mobile ECG [88]	Yes	No	Yes	Single	Single	High	Low	No	No	No
	PATHS [89]	Yes	No	Yes	Multi	Single	High	Low	No	No	No
	AWARENESS [90]	No	Yes	Yes	Multi	Single	High	High	Yes	No	No

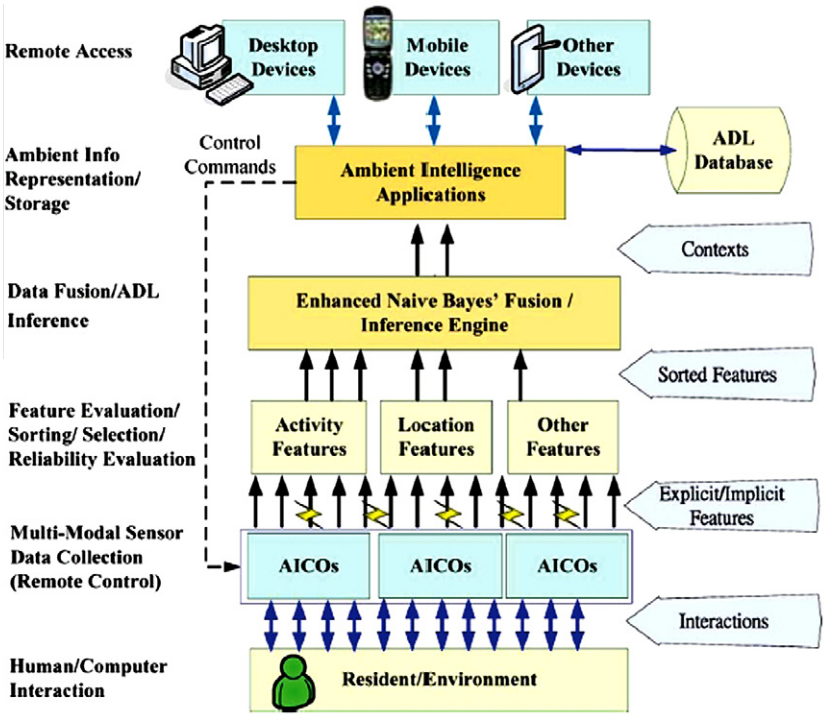

Fig. 3. Hierarchical system architecture for location-aware activity recognition [66].

instrumented with over 900 sensor inputs which include built-in wired sensors, motion-detection sensors and RFID tags. The subject carries an RFID reader bracelet. The results indicate that 10 infra-red motion detectors outperformed the other sensors on many of the activities, especially those which were typically performed in the same location. This is a more cost-effective solution although less accurate. The authors also note that the activities like "eating" and "reading" were difficult to detect and require the use of additional sensors and improved algorithms.

One important question to mention here is "How do we decide on the necessary activities to be tracked?". In most of the studies, the motivation behind the selection of the activities classified is not provided. There may be some certain activities that are specific to some disorders as in the case of epilepsy seizures; however, detecting activities like teeth-brushing or shaving [92] may not be extremely useful for pervasive healthcare systems. In that sense, more independent living oriented studies are worth mentioning. To begin with, the *CareNet Display* [51] is a conceptual digital Liquid Crystal Display (LCD) picture frame that has interactive features. It is an unobtrusive and user-friendly system. The main screen displays a picture of the elder's and icons for seven types of events ranging from daily activities including medication, meals, household needs to emergency situations like falls. The information on the screen is supposed to be collected by the sensors deployed around or provided by the members of the elder's care network. The caregivers interact with the display by touching the icons on the screen. The elder is able to choose and configure the information the caregivers are informed about. This privacy-respecting scheme is important and allows the users to have control over their private data. After configuring the system, the caregiver can monitor the daily activities or medication instantly or historically with five-day trend views.

Another activity monitoring system is the *Caregiver's Assistant* [14], which is designed to monitor the elderly in their home environment. Basically, the system works by equipping various items throughout the user's home (medicine bottles, toothbrushes, keys, etc.) with RFID tags. These tags along with a tag on the user's hand enable real-time monitoring of which items they are picking up. Time stamps, duration and patterns of use are extrapolated from this data and are compared to a baseline. All of this information is recorded automatically on electronic daily activity forms and presented in an application with graphs and charts. Thus, healthcare professionals are able to monitor any deviations from the elderly user's normal activities. This system may be useful for people with cognitive disabilities. The sensor networks are established throughout the user's home. When the user picks up an item, the tag on the item and the tag on the user communicate. The data is transmitted to a reader within the user's home. This could be a personal computer that has a connection to the Internet. The data is transmitted via RFID to the reader, over the Internet to the healthcare professional who monitors the data streaming in. The raw data coming into the system is translated via an activity tracking system that uses dynamic Bayesian networks and artificial intelligence technology to meaningful estimate information about what activities people are doing in the home.

RFID systems are widely used in activity recognition projects because of their technological maturity, decreased costs and availability, besides capability of battery-free operation with passive RFID tags. Although RFID systems do not have sensing capabilities yet, the *Wireless Identification and Sensing Project* (*WISP*) [67] explores the enhancement of passive RFID tags with sensors so that tags can also send sensor data to the readers. The tags capable of sensing are called wisps. The prototype design that is capable of sending one-bit accelerometer data is called the α-wisp. It uses ID modulation and by using a mercury switch, it can communicate two different ID's for two different inertial situations, therefore it is battery-free. In an Activities of Daily Living (ADL) recognition prototype, several household objects are tagged with α-wisps and RFID antennas are placed in room corners. The prototype requires about a thousand of objects to be tagged although typically less than 10 objects are actively used at any time. This indicates that for accurate classification, we need lots of objects to be tagged, however, the study is important in incorporating sensing technology into RFID technology in a power efficient-way.

There are also some studies that focus on disease specific activity classification which is of more importance in pervasive healthcare systems. The *LiveNet* [68] is an example of such systems and is a real-time distributed mobile platform. The system has three components: a mobile wearable PDA platform based on the MIThril architecture [93], a software architecture that allows the creation of distributed applications using context information, and a real-time context engine used for implementing light-weight machine learning algorithms that can run on a PDA and identify the user's context data and perform classification. The LiveNet system can be used for activity classification and has real world experiments on Parkinson's Disease (PD) and epilepsy patients. It can successfully differentiate between different symptoms of the illness: bradykinesia (slowness of movement) and hypokinesia (diminished motor activity) in PD case and idiosyncratic motions in epilepsy. A similar study on PD is also presented in [94]. In [95], machine learning techniques are employed for categorizing the abnormal human activity based on body-worn sensor data.

3.2. Fall and movement detection applications

Although falls and body movements are specific cases of activity classification, there is a significant research effort focusing on fall detection and body posture and gait analysis. This is due to the fact that accidental falls are among the leading causes of death over 65. Most of the studies in the literature make use of accelerometers and gyroscopes for identifying sudden falls. There are only a few studies that propose the use of unobtrusive ambient video cameras, because of the privacy issues. On the other hand, in the *Information Technology for Assisted Living at Home* (*ITALH*) [69] project proposes the use of video camera enabled phone only under emergency conditions. It is a fall detection system based on accelerometer data for elderly people. The sensor node's processor is capable of analyzing the accelerometer data in real-time and classifying events such as falls or other normal and abnormal events. When a fall is detected, the mote opens a connection to a Bluetooth capable camera phone and the sensor data is streamed to the phone. The phone makes a call to an emergency center if the user does not respond to the initial request made by the phone. In this way, the system provides rich visual information about the user when an abnormal situation is detected and he/she is unable to respond.

In a more typical application, a human activity monitor and fall detection system is presented in [70]. The system uses a single 3-axes accelerometer to identify human activities by using signal processing techniques. The base station mote gathers the accelerometer data and relays the data to the server computer for processing. The mobile mote carried by the user gives accurate results as 81% correct detection of a fall while running and resting when the mote is worn on the chest rather than on the wrist. This is not surprising when the identification is done by only a single acceleration sensor since the higher amplitudes will provide more distinguishable acceleration data.

Another issue in fall identification with acceleration data is differentiating a fall from other fall-like situations like jumping, lying or sitting down quickly on a chair. Moreover, the fall detection systems should be robust against different types of falls. Wang et al. [71] propose a fall-detecting system placing an accelerometer on the head level and using an algorithm to distinguish between falls and daily activities. The proposed algorithm can distinguish eight kinds of falling postures and seven kinds of daily activities including standing, sitting down, lying down, walking, jumping, going up (down) stairs, and jogging. Their algorithm tries to find the difference between the initial time when the body contacts the ground and the time the body is at rest. According to this difference, a fall decision is made. In another study, Leijdekkers et al. [72] propose to make fall decisions according to the position of the users after a large acceleration is observed. Large accelerations are not classified as falls as long as the position is upright or the accelerometer detects activity. This simplifying assumption of being inactive after a fall situation may not be realistic, since the person may be suffering pain and making the movements because of the pain.

One multi-modal fall detection system with location identification technique is *Smart Home Care Network* [52]. It is a multi-modal home-based monitoring application that uses both wireless sensors and image sensors. The sensor network contains a user badge node with accelerometers and voice transmission capability over IEEE 802.15.4, several image sensors to be used for situation analysis when an alarm is generated by the user badge, a network node with a phone interface to setup a communication link in the case of an emergency and other wireless nodes to increase the Received Signal Strength Indicator (RSSI) measurements' accuracy. When the user badge node detects a significant change in the accelerometers' data, it broadcasts an alarm message. By employing RSSI measurements, the approximate location of the user is detected and the most suitable image sensor node is activated for further posture analysis of the user. If the fall is confirmed via image processing, the network node with the phone interface dials the predefined care center number and con-

Fig. 4. HipGuard: a garment-integrated measurement system [73].

nects the user badge to the phone network via IEEE 802.15.4 radio link allowing the two way interaction. This system is more robust than systems that use a single accelerometer since it employs multi-modal sensing and reducing false alarm rate. Instead of continuous monitoring with image sensors, using them only under emergency conditions and only for confirmation purposes helps increasing both efficiency and privacy considerations.

Other than fall detection, there are also posture analysis applications. To give an example, *HipGuard* [73] is a posture detection system intended for the recovery period of eight to twelve weeks after a hip replacement operation. The system has seven sensor nodes placed on waist, thighs, shins and feet as depicted in Fig. 4. The central control unit collects and processes the data from the sensor nodes and produces alarms like audio signal or a haptic vibration if the position of the operated hip or the load put on the operated leg approaches the limits set by the healthcare professional. The sensors are integrated into the garment that helps unobtrusiveness and comfort of the system. In a similar study [96], a more obtrusive system which consists of seven sensor units each has a tri-axes acceleration sensor and three gyro sensors aligned on three axes, is proposed for gait analysis.

3.3. Location tracking applications

Location tracking for pervasive healthcare systems may serve both indoor and outdoor applications. In an indoor scenario, the location tracking system can be integrated for increasing the context-awareness of the systems and for efficiency. In an outdoor setting, it can be used for assisting people with cognitive disabilities or identifying the locations of people when an alarm situation has occurred like an epilepsy seizure. Since GPS is the most robust and widely available technique for outdoor location tracking and it does not properly work indoors, the development of indoor localization techniques is more worthy.

To begin with, Chang et al. [74] propose an RFID based way finding system for cognitively impaired patients. The system works by placing passive RFID tags in important locations where patients need to make decisions about the next action to take, such as turning right or left. Patients have to carry PDAs that have built-in RFID readers to identify the location by reading passive RFID tags and provide just-in-time directions to guide the patients to the destination also providing with spatial photos. The visited positions are tracked and logged and in case of anomalies, alarms are raised. This prototype application may suffer from the tag-reader communication problems due to shadowing effects and scalability of the system is limited because it necessitates the association of the places with the tags. Yet, in a hospital setting it can provide assistance to the patients who are having difficulties finding certain places.

The *Ultra Badge System* [75] is another location tracking application that is used in a hospital setting. In Ultra Badge, a 3D tag system designed to realize the location of the patients. When a patient is in a specific area where a fall is most likely to occur, the system alerts the caregivers beforehand. The Ultra Badge System consists of ultrasonic receivers embedded in the environment and wireless ultrasonic emitters placed on objects as depicted in Fig. 5. Since the positions of the receivers are known, the emitters are located by using the multi-lateration technique. The system implementation has two subsystems: the wheelchair locator and ultrasonic radar. With the former, when a patient using a wheelchair carrying an ultrasonic emitter approaches a "detection area" where a fall is most likely to occur such as at the entrance of a toilet, the nurse is notified. The latter subsystem aims to detect the activities of the patients in their beds by using ultrasonic pulses.

ZUPS is a ZigBee and ultrasound based positioning system that provides multi-cell coverage [76]. Besides ultrasound technology, ZigBee is preferred because of interoperability with other ambient intelligence applications like home automation. The system basically uses ZigBee and ultrasound to measure distances between mobile devices carrying tags and beacons with known locations; however, it uses proximity and multi-lateration localization methods simultaneously. The coexistence of ZigBee and ultrasound minimizes the infrastructure needs for ultrasound systems. Although its main purpose is to warn when an alarm situation occurs, the system can provide other functions such as guidance and spatial orientation training inside a large building for the elderly and people with disabilities. The alarm situations like falls and different walking patterns can be detected by the mobile device which integrates accelerometer and communications (ZigBee) module as suggested by [97]. In their ZigBee based localization system, the ZigBee tag sends out a one-hop broadcast to learn the addresses of all reference nodes that are within radio range. After learning the adjacent ZigBee reference nodes, the tag sends a one-hop blast broadcast message to every reference node requesting the average RSSI values. The reference nodes perform the running average of RSSI of the broadcast messages received from any particular ZigBee tag and then they feedback the calculated RSSI values and their own coordinate to the ZigBee tag. After the ZigBee tag collected the RSSI and coordinates from reference nodes, it uses this information to calculate its own position. Then it sends the calculated relative coordinate back to the ZigBee Gateway. The tag's position is estimated by itself, the decentralized mechanism is a distinguishing feature in contrast with the traditional indoor techniques. As for the concern of fall-detecting signal transmission, multi-hop routing allows jumping through outer clustered tree, which provides a reliable data transmission via alternative paths to ensure the falling signals destined to the back-end emergency alert system.

ALMAS [77] project integrates location tracking technology with video analysis and wireless multimedia technologies to create an environment that provides healthcare for the elderly. It consists of the following physical components: A wireless wearable unit and a RFID tag attached to the patient, which store and transmit the patient's vital signs and location, wireless transceivers, which communicate with the RFID tags and the wearable units worn by the patients to track and locate them, video cameras, which constantly monitor the patients' activities and record them when a problem is detected by the tracking system, a PC with video capture capability, to which all the hardware are connected and on which all the software run, and a PDA capable of receiving alerts, video clips, and vital signs of the patient. The patient's location is determined by the relative strength of the radio frequency (RF) signals received by the RFID transceivers. ALMAS' video cameras continuously record the activities of the patient and automatically detect if there is a situation that requires attention by the healthcare professional. Examples of such situations include: patients that are perceived to be leaving

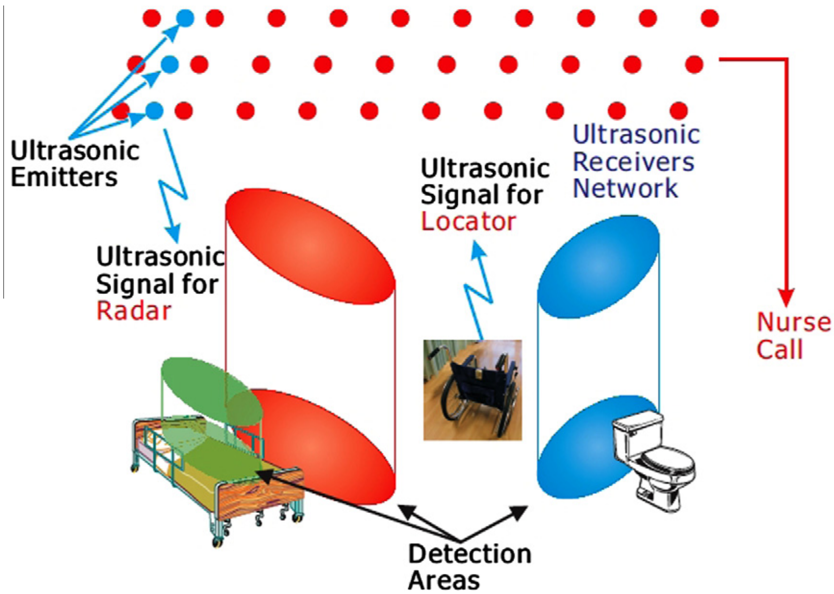

Fig. 5. Schematic diagram of the Ultra Badge System [75].

the room or hallway towards an unauthorized area or patients that are found in unusual conditions like lying on the floor for an extended period of time. If such motion is detected and the patient is perceived to be crossed the line between the room and the common area, the second camera begins to monitor patient's activity and generates signals to alert the healthcare professional. The alerts and associated video clips are wirelessly transmitted to the healthcare professional's PDA. The healthcare professional responds to the event by monitoring the video clip and taking appropriate action.

All of the studies mentioned use RSS based techniques. The RSS values obtained from RFID tags or ultrasonic tags are used for determining the location. Yan et al. [78] propose a technique called passive positioning which makes use of the people as a radio scattering object and their effect the Received Signal Strength (RSS) of fixed sensor nodes. The location of the mobile object is estimated by the change in RSS of a set of sensor nodes. If some of the parameters of RSS such as amplitude, local mean, or local variance of the links change more than a given threshold, a moving object or person can be detected, and the position can be coarsely determined according to the set of receivers or variable RSS and their cross-correlations. These types of systems may be more suitable when only the presence information is enough, since obtaining the exact position in noisy environments is extremely hard and error-prone.

3.4. Medication intake monitoring applications

Medication noncompliance is common in elderly and chronically ill especially when cognitive disabilities are encountered. Therefore, medication intake monitoring is essential. One of the early prototypes developed by Moh et al. [79] aim to control the medicine intake of the elderly with the combined use of sensor networks and RFID. It consists of three subsystems: The Medicine Monitoring Subsystem is used for medicine bottle identification using high frequency (HF) RFID tags and the amount of the medicine removed by the user is tracked by a weight scale. The system is able to determine when and which bottle is removed or replaced by the patient and the amount of medicine taken. The patient wearing an Ultra High Frequency (UHF) RFID tag is identified and located by the Patient Monitoring Subsystem and the system is able to alert the patient to take the necessary medicines. Finally, the Base Station Subsystem is responsible for message relay to the Base Station Personal Computer (PC). The Base Station software tasks include simulating a display and its GUI for the patient; determining when medicine is required; and maintaining various interactions between the Medicine Mote and the Patient Mote.

The *iCabiNET* [80] solution makes use of the smart RFID packaging that can record the removal of a pill simply by breaking an electric flow into the RFID's integrated circuit. iCabiNET is an indoor application that is also interfaced to a residential network, in this way, the medicine intake can be monitored over the residential network by using the RFID readers at home. The system is capable of monitoring the drugs that are bought by the user and when the presence at home is detected the smart appliances, such as TV, can be used to inform the patient about the usage and dosage. Furthermore, an interactive TV application can also be integrated with the system that allows the purchase of the new packet of the drugs when the supply is decreased. As an alternative scenario, the iCabiNET system can be integrated with the cellular network or ordinary telephone network in order to remind the patients to take their medication correctly.

Another intelligent packaging prototype is proposed and developed by Pang et al. [81]. The system is capable of both remote medication intake monitoring and vital signs monitoring. The intelligent package prototype, called the *iPackage*, is different from RFID attached intelligent packages in that it uses an array of Controlled Delamination Material (CDM) films and its control circuits are added. The CDM film is a three-layer foil composed of aluminum bottom and top layers and an adhesive middle layer made of electrochemical epoxy. When a voltage higher than a particular threshold is applied on the bottom layer and top layer, an electrochemical reaction occurs in the middle layer. When the voltage is applied for a certain amount of time, the epoxy layer is destroyed and delaminated. Therefore, the iPackage sealed with a CDM film can only be opened by the special control appliance which also enables the control of the dosage. The identification of the correct pill is accomplished by RFID. The prototype design of CDM and tagged capsule package is depicted in Fig. 6.

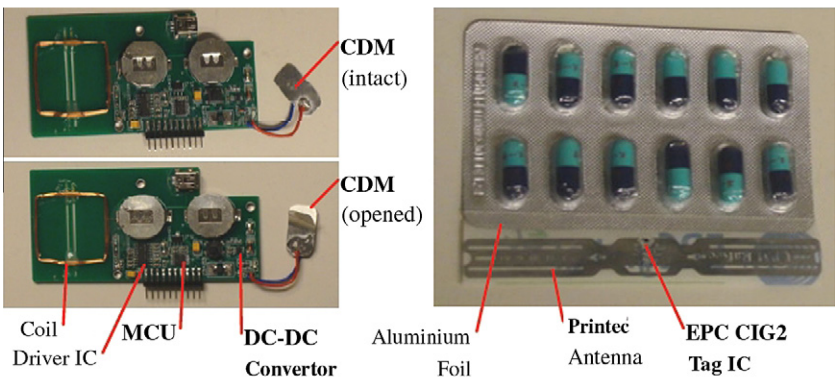

Fig. 6. A Prototype of iPackage [81].

3.5. Medical status monitoring applications

Monitoring the medical status of the people is the most widely studied application type of pervasive healthcare systems. The commonly used vital signs are ECG, pulse oximetry, body temperature, heart rate, blood pressure. The acceleration data is also used together with these vital signs in some studies. Most of the studies focus on capturing and sending the data to a remote site for further evaluation.

MobiHealth [82] is one of the early projects that integrates all the wearable sensor devices such as PDA's mobile phones and watches that a person carries around during the day. The sensors continuously measure and transmit physiological data together with the audio and video recordings to health service providers in order to provide fast and reliable remote assistance in case of accidents. MobiHealth is important in being one of the early studies proposing the convergence of different network systems like BAN, PAN and WAN to enable personalized and mobile healthcare.

CodeBlue [83] is a hardware and software platform developed at Harvard University. The hardware design part includes the design and development of a mote-base pulse oximeter, two-lead ECG, and a motion analysis sensor board. The software architecture is based on a publish/subscribe routing framework. CodeBlue aims to provide coordination and communication among wireless medical devices in an ad hoc manner. The sensors do not publish data at an arbitrary rate, because the wireless channel's bandwidth is limited and they filter the data locally. Moreover, when publishers and subscribers are not within radio range, multi-hop routing is used. Since the publishers and subscribers are mobile, mobility must be taken into account when establishing routing paths. Also, a discovery protocol is used for CodeBlue nodes to discover each other and determine the capabilities of their sensor devices. Moreover, the system integrates a localization system called MoteTrack [98] which is an RF-based localization system used for locating the patients and healthcare professionals. CodeBlue project is one of the most comprehensive projects in the literature which includes mote design, software architecture design, ad hoc network design and multi-hop communication together with location tracking.

AlarmNet [84] is a wireless medical sensor network system prototype composed of five components. The mobile body sensor network is responsible for the physiological monitoring and the location tracking functions. The mobile body sensors include heart rate, oxygen saturation, and ECG that are developed in CodeBlue project. The emplaced sensor network provides a spatial context and environmental information such as temperature, motion, humidity. The designers use indoor temperature and luminosity sensors for this purpose. The AlarmGate connects the wireless sensor and IP networks and also responsible for privacy, power management, query management, and security. It acts as a gateway between the data accumulation and storage parts. The data is stored in the back-end for long-term analysis and mining. The graphical user interface that runs on a PDA displays accelerometer data, patient pulse rate, and environmental temperature and allows caregivers to query sensor data. The PDA devices are carried by healthcare professionals and they are able to remotely monitor the vital signs of the patients.

The *LifeGuard* [85], which was developed for astronauts in the first place, can also be used for general vital signs monitoring. The system is comprised of three components. The sensors part can support different types of sensors such as ECG, respiration, pulse oximeter, and blood pressure. The sensor data are collected and stored by a wearable device called Crew Physiological Observation Device (CPOD) as depicted in Fig. 7. It has 3-axis accelerometers and skin temperature sensors internally. The base station part is a Bluetooth capable Tablet PC. It can display and

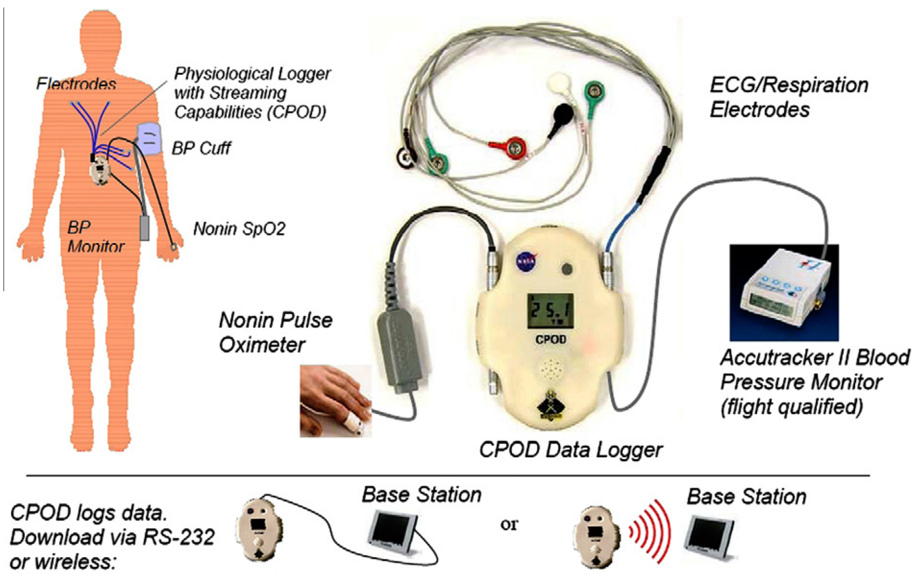

Fig. 7. LifeGuard system diagram [85].

also store the data streaming from CPOD for further evaluation.

Zhou et al. propose a three layer network structure for a pervasive medical supervision system based on wireless sensor networks [86]. The first layer is the medical sensor layer providing information such as the oximetry, the heart rate/pulse and the blood pressure. The medical sensors form a star schema network with a gateway node elected by either a self-organizing protocol or manual configuration. The second layer provides reliable transmission. If the patient is at home, the physiological data is transferred to one of the nearest wireless nodes that are emplaced in the house. These nodes not only relay the data to the PC with an Internet connection in a multi-hop manner but also provide contextual data such as temperature, and the patient's video/picture in emergency situations. When the patient is outside, the relay mission is accomplished by a mobile phone or a PDA device. The third layer of the system is responsible for the aggregation of physiological data in a remote medical center for analysis and providing feedback data back to the patient through a mobile phone, a PDA or web services.

The mentioned projects are sophisticated and comprehensive research studies. There are also simpler prototype designs in the literature worth mentioning for addressing different types of users. In [87], for instance, several prototypes are presented by a group of researchers. As an example, *FireLine* is designed for monitoring cardiac measurements of firefighters for being able to take the necessary actions in the case of abnormality. The device is composed of a wireless sensor, a heart rate sensor and three electrodes. The heart rate measurements are transmitted to a base station mote attached to a portable laptop where the data are stored and processed. In the case of an abnormality, the GUI alerts the caregiver about the firefighter's health status. Another example is the *Baby Glove* [87] which consists of two integrated sensor plates placed on infant's upper torso, which contain a temperature sensor and electrodes that monitor the infant's pulse rate and hydration. The device is comprised of two motes. One is connected to the infant's clothing and the other to a base station computer. The first mote collects the vital sign information coming from the sensors and transmits them wirelessly to the second mote which is connected to the base station computer for processing. If the vital signs are over the limits, the caregivers are alerted. *LISTENse* is a prototype that enables the hearing impaired to perceive the critical sound information like doorbell or smoke alarm. It is comprised of at least two wireless sensor network motes. The user carries the mote called the "Base Station" on his wrist or belt which has a vibrator and Light Emitting Diodes (LEDs). Each of the other motes having a microphone called the "Transmitter" is placed close to the sound source that it is to be heard. The Transmitter periodically samples the microphone signal and compares the sample with a reference user-defined value. When the measured signal is over the reference value, an encrypted message is sent to the Base Station to prevent the false alarms caused by any similar existing wireless devices in the environment. Upon receiving the encrypted activation message, the Base Station extracts the Transmitter address and turns on the vibrator and corresponding LEDs. Alternatively, it may display an appropriate text message on its LCD screen.

There is a significant research effort on cardiac monitoring. Especially the mobile ECG measurement systems are gaining importance since their extended usability. In [39], the authors describe a cardiac healthcare system that can utilize both Wireless Local Area Network (WLAN) and Code Division Multiple Access (CDMA) technologies to transmit data. When the ECG sensor on the patient's body detects a WLAN, all data are directly routed through the Access Point (AP) to the server PC. When a WLAN is not present, a cell phone with a prototype wireless dongle that is capable of performing a simple electrocardiogram diagnosis algorithm is used. The dongle collects the physiological data coming from the sensor and an application running on the cell phone analyzes this data locally. Only when an abnormality is detected, the data is transferred to the cellular network using TCP/IP to prevent congestion. The proposed work is important in its effort on providing continuous roaming; however the limitations of cell phone resources prevent ECG analysis algorithm to work appropriately. Yang and Yang propose an adaptive algorithm for computing the heart rate and its variance from ECG data for a similar wearable ECG system [99].

Mobile ECG [88] is another ECG measurement and analysis system which uses a smart mobile phone as a base station. The mobile ECG recording device sends the data to the mobile phone via Bluetooth. The mobile phone records and analyzes the received data. If any abnormality is detected the ECG data is sent to a server for further analysis by the healthcare professionals. If requested, the mobile phone is able to display the ECG signal and the heart rate on the screen. A similar work using a PDA as the base station is also represented in [100].

One final example of ECG measuring systems is *Physical Activities Healthcare System* (PATHS) [89] which includes a wearable wireless sensor unit (W2SU) that has ECG and dual-axis accelerometer sensors, a hand-held Bluetooth device to collect data from the wearable unit. The wearable unit has a Secure Digital Memory Card (SD Card) interface and a high speed USB port; therefore, it can also record physiological data to be transmitted to the hand-held device for further use or can transmit raw ECG data to a monitor for real-time display. Furthermore, the hand-held device can relay data and abnormality alarms to the Internet for the use of healthcare professionals. With these features, it behaves both as a real-time and as an offline physical activities monitor.

There are also some studies for identification of complications of some diseases such as epilepsy seizure. *AWARENESS* [90] is an example context-aware health application that is designed to detect and react to epilepsy seizures. In a neurological body area network prototype, the ECG data captures an epilepsy seizure; however, without the context information the change in the heart rate cannot be reliably attributed to an epilepsy seizure since it may be due to motion. Therefore, the contextual information on the location of the patient and the location of the healthcare professionals are combined with the availability of the healthcare professionals and the most appropriate professional is routed to the patient having an epilepsy seizure in AWARENESS. In order to enable context-awareness, a rule language and an engine are designed as well as an infrastructure for discovering and dynamically binding sources with the application.

4. Challenges and open research problems of the WSN solutions for healthcare

In this section, we present the challenges observed while designing pervasive healthcare systems and state the open research problems of the surveyed systems. There are numerous challenges of wireless sensor networks in all layers. In this survey, we approach these challenges with a healthcare specific perspective. The stated challenges are selected must be studied for fully enjoying the benefits of pervasive healthcare systems using wireless sensor networks.

4.1. Hardware level challenges

4.1.1. Unobtrusiveness

The design and development of wearable sensor devices without violating unobtrusiveness is still a significant challenge. When the patients have to carry sensors attached on their bodies as fall detection systems described in [70] and FireLine [87], unobtrusiveness becomes a major challenge among many others. The need for integrating different sensors into one solution makes it harder as in the sensor units of LiveNet [68] and PATHS [89]. These body-worn sensor devices are heavy and highly obtrusive devices, whereas the bandage type ECG sensors described in [21] and watch-shaped activity recorder in [22] are much more easy-to-bear devices. The integration of the sensor devices with the fabric is studied in several publications [101–103].

4.1.2. Sensitivity and calibration

Sensitivity of the sensor devices is important especially when the users wear the sensors under harsh environments like in a fire situation or exercising. The sweat can affect the transducers of the sensor devices negatively, causing the reduction in the sensitivity of the body-worn sensors or requiring recalibration of the sensors. Gietzelt et al. [104] propose an automatic self-calibration algorithm for triaxial accelerometers. Yet, the self-calibration and sensitivity enhancement algorithms are still needed for sensor devices different than accelerometers. Low-maintenance and highly sensitive vital signs monitoring sensors will attain importance as pervasive healthcare systems evolve.

4.1.3. Energy

One of the bottlenecks of sensor devices is the batteries. For indoor environments, rechargeable batteries may be the remedy in some cases, whereas recharging the batteries may be burdensome especially for the elderly. Considering the likelihood of forgetting to recharge the batteries of several sensors, this is a significant issue to be solved. Although there is much effort on designing low-power sensors to minimize this bottleneck [21], we still need energy scavenging techniques. The solar cells that can provide up to 15 mW/cm^2 under direct sun, cannot be used with body-worn wireless sensors because sensors are preferred to be placed under the clothing. Therefore, motion [105] and body heat [106,107] based energy scavenging techniques should be studied for healthcare systems.

4.1.4. Data acquisition efficiency

The data collection rate in pervasive healthcare systems is high. The development of efficient data processing techniques are of great importance. In some cases 3-lead ECG may not be sufficient for identifying a cardiac disease or a single 3-axes accelerometer may not be capable of classifying all activities of the people. In these cases, more sensors will be needed and the gathered data will increase. The real-time acquisition and analysis of the physiological data is essential. Besides, time-stamping and ordering of the events, synchronization of different sensors are open research problems [6]. Finally, integrating different types of sensors, like RFID tags, implantable body sensors and wireless sensors necessitates the development of modular architectures.

4.2. Physical layer challenges

4.2.1. Error resilience and reliability

Low transmission power and small antenna sizes of wireless sensor devices causes reduced Signal-to-Noise Ratios (SNR) thus causing higher bit error rates and reducing the reliable coverage area. However, the reliable transfer of data in medical monitoring systems is vital. Therefore, error resilient network coding schemes for medical data transmission should be developed for increasing network reliability. Marinkovic and Popovici [108] propose a network coding technique for a TDMA based protocol. It lets every sensor to transfer data through two relays and the relay nodes XOR the packets before sending. Although they have showed the improvements in the packet loss rate through simulations, the real deployments for measuring physiological signals, such as ECG and EEG and improving the proposed system accordingly are left as future works. The reliable data transmission should be studied thoroughly for low power body area sensor networks.

4.2.2. Interoperability

The integration of several sensing devices operating at different frequencies raises an interoperability problem. Communication between different devices occupies multiple bands and use different protocols. This situation may cause interferences among different devices especially in the unlicensed Industrial, Scientific and Medical (ISM) radio bands. The pervasive healthcare systems must be designed with interoperability provisioning between different devices [6].

4.2.3. Bandwidth

The bandwidth available for data communication for wireless body area networks is relatively low. Although, new sensor nodes can operate at 250 Kbps, due to duty cycling mechanisms for lowering the power consumption lowers the actual available bandwidth. If the sensor nodes operate with a duty cycle of 10%, then they are actually transmitting data at only 10% of the time. This situation may pose difficulties especially when there is huge amount of data like in the case of transmission of a diagnostic medical imaging data which can require up to Mbit/s level capacities. For this reason efficient compression algorithms should be developed for multimedia data transmission. These compression techniques should also be lightweight enough for running on a sensor node which does not have high performance processing units and memory.

4.3. MAC layer challenges

Besides regular MAC layer challenges of WSN like energy efficiency [109], there are challenging problems that are specific to healthcare monitoring. To begin with, Quality of Service (QoS) requirements of emergency traffic are needed to be studied for healthcare monitoring applications. In [110], Benhaddou et al. propose a MAC scheme for healthcare which incorporates a preemptive service scheduling algorithm into the 802.11e QoS MAC to provide the highest and preemptive channel access precedence for medical emergency traffic. The QoS-aware MAC protocols for low power wireless sensor networks like 802.15.4 are still needed to be studied from a healthcare specific perspective.

In most cases, we can safely assume that there will be a nearby access point (base station) since these systems are generally connected to a gateway before sending data over the WAN. In one-hop communication schemas, TDMA based MAC protocols can make life easier. On the other hand, as developed in CodeBlue [83] project, there are also multi-hop communication networks. These are also of great importance due to their ability of extending the boundaries of the service. For real pervasive healthcare monitoring, we will need multi-hop wireless communications between the sensor nodes eventually. Therefore, delay optimizing MAC design will be essential. Demirkol and Ersoy describe a method for optimizing delay, in which the optimum contention window size is approximated by individual sensor nodes in a distributed manner based on the estimated number of contenders [111].

Healthcare monitoring applications require emergency event reporting besides periodic physiological data reporting. Under emergency conditions, the emergency data should be guaranteed to be delivered with a reasonable delay. For this purpose, emergency data prioritization mechanisms should be developed. Moreover, the fairness among different emergent situations should be considered. The event based fairness scheme proposed by Durmus et al. [112] is an example for video sensor networks. The prioritization and fairness mechanisms for vital signs monitoring applications are open research issues.

4.4. Network layer challenges

Delay optimizing and energy-aware routing protocols are the most important open research challenges for applications of wireless sensor networks for healthcare monitoring. The convergent traffic inherent in wireless sensor networks may cause choke effect at the nodes closer to the base station. For this reason, load balancing routing protocols need to be developed. Moreover, when multimedia traffic is encountered with the emergence of multi-modal sensor networks for healthcare monitoring applications, congestion avoidance and rate control issues become significant [113]. These techniques should also be integrated with data compression techniques for better utilization.

For in vivo sensor networks, there is also the problem of sensor nodes' temperature, since they may harm the tissue when they are overheated. For addressing this challenge Tang et al. [114] propose a thermal-aware routing protocol (TARA) for implanted biosensor networks. Yet, these protocols should avoid the degradation on delay performance. Moreover, for reliable data delivery, multipath routing protocols for medical sensor networks should be studied.

4.5. Transport layer challenges

Since healthcare applications deal with life-critical data, a lost frame or packet can cause an alarm situation to be missed totally or misinterpreted. Consequently, reliable data delivery is required. Although there are reliability mechanisms at different layers such as automatic repeat request (ARQ) at MAC layer, critical WSN applications such as healthcare monitoring require total end-to-end reliability mechanisms [115]. The reliability for medical application may require either packet level or event level solutions. For periodic traffic, packet level reliability is essential whereas for emergency event reporting such as a sudden fall detection then event reporting is more important than individual packet reporting. Designing cross-layer protocols for ensuring reliable delivery for different type of traffic is also essential.

The congestion and flow control mechanisms at the transport layer are also rare. For instance, the Event-to-Sink Reliable Transport (ESRT) protocol [116] aims to guarantee a sufficient number of packets to be delivered. In that sense, ESRT may be suitable for event reporting applications. On the other hand, for periodic physiological data reporting such as ECG, or heart rate, every single packet has to be delivered reliably; therefore transport protocols addressing this issue are still needed to be developed.

4.6. Application layer challenges

We have already addressed some of the challenging issues in Section 2.5 which are studied in the literature more frequently. On the other hand, organizing the data and producing meaningful information that evolve into knowledge is one of the hardest challenges at the application layer. The application layer being at the top surface is expected to have a coordinating mission also. In this context, the organization of ambient sensor data, medical data and other contextual data must be held by this layer. The organization of data is crucial and should be studied deeply. Moreover, robust machine learning algorithms are needed for self-learning, autonomous systems replacing rule-based and static systems.

4.7. Layer independent challenges

There are some challenges that are not directly related with a specific layer or directly related with all. These challenges and related hints for their solutions are provided in the following subsections.

4.7.1. Security

The fundamental security requirements of the overall system are confidentiality, data integrity, accountability, availability, and access control. For assuring these security requirements, encryption methods can be used which raises the challenge of developing efficient key management protocols. In [117], an elliptic curve cryptography for key distribution, in order to decrease energy consumption is proposed. Another challenging issue with the security requirements arises when the patients are unconscious. Since obtaining passwords may not be possible in those cases, biometric methods may be used for accountability [118]. The physiological signal based authentication scheme proposed in [31] is an example. It generates identity information for mutual authentication from an ECG-like measure called photoplethysmogram (PPG) captured simultaneously at two different parts of the body. Finding unique biometric features to be used for identification purposes is a further challenge in this context.

4.7.2. Privacy

Authorization of the users in the system should not be overlooked and the users should have autonomy and control over their data of any type [50]. Besides, especially in image processing applications which are becoming more available from day to day, the privacy-preserving methods should be developed for the comfort of the monitored people. On-node processing of images can be a solution in which no images are transferred, only the information about the image is sent over the network. Srinivasan et al. [119] point at a privacy leak called Fingerprint and Timing-based Snooping (FATS) attack in wireless sensor systems even though the wireless communication is encrypted. This privacy flaw enables the attacker to monitor the ADL of the people only with two pieces of information, namely the timestamp and the fingerprint of each radio message. Although, the authors propose a hybrid scheme for thwarting this kind of attack they also note that there may be many potential physical-layer privacy attacks on wireless ubiquitous systems to be studied.

4.7.3. User-friendliness

The users should embrace the system for full satisfaction. Casas et al. propose user-modeling involvement to enhance the interaction [120]. The development of natural interfaces between a diverse group of people and pervasive systems are crucial. In [121], the authors surveyed their level of user-friendliness among a small elderly group and concluded that their interface should be revisited. The needs for different groups should be identified clearly, which is not a trivial task. For instance, patients with cognitive disabilities have different interaction characteristics with the system than patients with diabetes. For instance, the user interface for the handicapped and the elderly must be based on voice, gesture, and visual animation, and must avoid any kind of particular skills. The interface for healthcare professionals should output medical data such as emergency situation indicators and behavioral patterns of the people under observation in a domain-specific notation. The healthcare professionals and caregivers should also have user-friendly and natural interfaces with immediate response capabilities.

4.7.4. Ease of deployment and scalability

Similar to user-friendliness, developing easily deployable pervasive systems is also an essential and nontrivial challenge. When the number of patients and caregivers increase, the scalable and easily deployable applications that can also support multiple receivers will attain much importance. Pervasive healthcare monitoring systems generally require the simultaneous use of several sensor devices, communication devices and software. With these diverse components, ease of deployment becomes a challenge to be considered. For this purpose, a software as a service approach could be used for both scalability and ease of deployment, together with small and easily configurable sensor devices. The system must support addition of new components at runtime, in order to adapt the system to changing disabilities over time. The software platforms and distributed services will be needed for seamless integration of the hardware and the application levels and interoperability among these will be essential [122,123].

4.7.5. Mobility

The aim of health monitoring is to let people to survive an independent life with high-quality healthcare services. The use of sensors and sensor networks for this purpose is not new [124,125] however, the emergence of wireless sensor networks has enabled the development of applications which ensure and encourage the mobility of the users. In this way, the wireless sensor network technologies enable the ubiquity of healthcare systems. Providing mobility necessitate the design of multi-hop, multi-modal, ad hoc sensor networks which brings the challenges mentioned in the previous subsections along with the location-awareness challenges.

5. Conclusions

Given the importance of addressing ways to provide smart healthcare for the elderly, chronically ill and children, researchers have started to explore technological solutions to enhance health and social care provision in a way which complements existing services. In this study, we have evaluated the examples of how people could benefit from living in homes that have wireless sensor technologies for improved quality of life and outlined issues to keep in mind during their development. We have surveyed systems for acquiring and interpreting context information for the ubiquitous deployment of wireless sensor networks. Results from these works suggest a strong potential for wireless sensor networks to open new research perspectives for low-cost, energy-efficient ad hoc deployment of multi-modal sensors for an improved quality of medical care. In future smart home environments, there will be multi-modal sensor solutions that incorporate the benefits described, however, there are still challenges to overcome to achieve these context-aware, pervasive healthcare applications. We have provided an analysis of these challenges from a healthcare perspective of WSNs. A combination of different sensing modalities like video sensing, RFID, medical sensors together with smart appliances and remote monitoring ability will lead context-aware, pervasive healthcare applications to become within the reach of ordinary users.

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