RFID ENHANCED WIRELESS SENSOR NETWORKS FOR HEALTHCARE MONITORING

by

Hande Özgür Alemdar

B.S., Computer Engineering, Boğaziçi University, 2004

Submitted to the Institute for Graduate Studies in
Science and Engineering in partial fulfillment of
the requirements for the degree of
Master of Science

Graduate Program in Computer Engineering
Boğaziçi University
2009

ACKNOWLEDGEMENTS

Firstly, I would like to thank my thesis supervisor Prof. Cem Ersoy not only for his guidance throughout this thesis but also for his mentorship throughout my life. Without his efforts, for me to pursue an academic career would not have been possible. I also would like to thank him for all research enhancement mechanisms he provided : gözleme@Hisar, balık@Kandilli, pizza@Popüler, together with his invaluable support.

I would like to thank the members of the thesis jury, Assoc. Prof. Ata Akın and Assist. Prof. Haluk Bingöl for their valuable time and improving comments for making this dissertation better.

I also thank TAM project steering committee for their willingness for hosting our testbed at TAM building at Kandilli Campus.

I deeply thank Atay Özgövde and Yunus Durmuş for helping me with nearly everything related with this thesis. They never gave up answering my never-ending questions and they were my saviors at the most desperate moments of dealing with OPNET. Also, I am really grateful to Gökhan Remzi Yavuz and Ozan Özen for their help with the design requirements and running up the testbed.

I would like to thank to all friends in NETLAB and SATLAB (Nuri, Özlem, Derya, Didem, Şükrü, Birkan, Suzan, Seçkin, İlker, Gaye, Itır ...) and all other members of Computer Engineering Department for the nice times spent together. Special thanks to Rabun Koşar for the music and dance and for making me angry and making me cheerful. I cannot think of CMPE without him.

My very special thanks are for my family. They have provided all the love, support and trust I needed throughout my life.

Lastly, thank you my better half Serdar, for everything you do and do not.

This research is supported by Scientific and Technical Research Council of Turkey (TUBITAK) under the grant number 108E207 and also supported by BAP under the grant number 09A101P.

ABSTRACT

RFID ENHANCED WIRELESS SENSOR NETWORKS FOR HEALTHCARE MONITORING

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 engineering and healthcare application industries. In-home pervasive healthcare systems provide rich contextual information and alerting mechanisms against odd conditions with continuous monitoring. This minimizes the need for caregivers and help 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. In this thesis, we designed an indoor monitoring environment, namely *WeCare*, and showed the applicability of multi-modal sensor network technologies on healthcare monitoring. Besides, we performed several simulations on the capabilities of the Video Sensor Networks for healthcare monitoring in an outdoor setting. The results exhibit that their capabilities are limited. Therefore, reducing the number of the frames carried by the network is the primary objective. For this reason, we proposed several enhancements for reducing the traffic load on the network for better performance.

RFID is a very mature technology that has already been used in many areas. The RFID enhanced Video Sensor Networks reduces the network traffic load. Moreover, the proximity of the healthcare professionals who are also moving in the surveillance is also used as a frame reduction mechanism. Finally, for assuring the reporting of the emergency events in low latencies, we propose a queueing mechanism and evaluated its performance through simulations.

ÖZET

SAĞLIK GÖZETİMİ İÇİN RFID DESTEKLİ TELSİZ ALGILAYICI AĞLAR

Yaşam kalitesini iyileştirmede kullanılabilecek seviyeye gelen kablosuz telsiz ağ teknolojileri, bilgisayar ve sağlık uygulamaları sektörlerinde önemli bir araştırma alanı haline gelmiştir. Ev içi yaygın sağlık sistemleri, sürekli izleme sayesinde, zengin içeriksel bilgi sağlama yanında, uyarı düzenekleri ile olası sıradışı durumları tespit edebilmektedir. Bu durum, yaşlı ve hastaların bakıcılara olan bağımlılıklarını en aza indirmenin yanı sıra, ebeveynleri çalışmak durumunda olan küçük çocuklar ve bebekler için de daha kaliteli bir bakıma olanak vermektedir. Bu tezde, çok kipli algılayıcılardan oluşan ağların sağlık gözetimi uygulamalarında uygulanabilirliğini göstermek için *WeCare* isimli bir izleme ortamı yarattık. Bunun yanında, video algılayıcı ağların, açık alanlardaki sağlık gözetimi uygulamalarında kullanılabilme yeterliklerini benzetim yoluyla sınadık. Sonuçlar video algılayıcı ağların kabiliyetlerinin sınırlı olduğunu göstermektedir. Bu nedenle, ağda oluşturulan video çerçevelerinin sayısını azaltmak önem kazanmaktadır. Ağdaki trafik yoğunluğunu azaltarak başarımı iyileştirmek için çeşitli iyileştirmeler önerilmiştir.

RFID birçok alanda kullanılan olgunlaşmış bir teknolojidir. Video algılayıcı ağların RFID tarafından geliştirilmesi ağdaki trafik yoğunluğunu azaltmak için kullanılmıştır. Bununla birlikte, gözetim alanında bulunan sağlık görevlilerinin hastalara yakınlığı da video çerçeve sayısını azaltmak için kullanılan teknikler arasındadır. Son olarak, aciliyet gerektiren durumlarda üretilen video çerçevelerini hızlı ve güvenilir şekilde ulaştırmak için bir kuyruklama yöntemi önerilmiş ve başarımı benzetim yoluyla değerlendirilmiştir.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS/ABBREVIATIONS

d	Random variable representing the distance between two random points
d_t	Attention distance
D_1	Length of the shorter side of the surveillance area
D_2	Length of the longer side of the surveillance area
$f(d)$	Probability density function of d
$F(d)$	Cumulative distribution function of d
g	Acceleration due to gravity
N	Number of healthcare professionals
$P(A)$	Probability of attention
$p(N,k)$	Probability of a patient being monitored by k out of N healthcare professionals
$p(x)$	Binary attention probability function
α	Deviation angle
μ	Mean of the normal distribution
ζ	Shape parameter
ξ	Ratio of d to D_1
σ	Variance of the normal distribution
AAS	Augmented Awareness System
AD	Alzheimer's Disease
ADL	Activities of Daily Living
ADSL	Asymmetric Digital Subscriber Line
AmI	Ambient Intelligence
AP	Access Point
BAN	Body Area Network
CATV	Cable Television
CDMA	Code Division Multiple Access

CMOS	Complementary Metal Oxide Semiconductor
CPOD	Crew Physiological Observation Device
DC	Duty Cycle
ECG	Electrocardiogram
EFBQ	Emergency Frame Based Queueing
FCFS	First Come First Serve
FoV	Field of View
FPS	Frames Per Second
GML	Graphical User Interface and Main Logic
GPS	Global Positioning System
GPSR	Greedy Perimeter Stateless Routing
GRS	General Reminder System
GSM	Global System for Mobile Communications
GUI	Graphical User Interface
HF	High Frequency
ITALH	Information Technology for Assisted Living at Home
JPEG	Joint Photographic Experts Group
LCD	Liquid Crystal Display
LED	Light Emitting Diode
LF	Low Frequency
MAC	Medium Access Control
MAETTS	Mobile Agent Electronic Triage Tag System
MANET	Mobile and Adhoc Network
mPCA	Mobile Patient Caregiver Assistant
NFC	Near Field Communication
OPNET	Operations Network
PAN	Personal Area Network
PATHS	Physical Activities Healthcare System
PC	Personal Computer
PD	Parkinson's Disease
PDA	Personal Digital Assistant

PIR	Pyroelectric Infra Red
PWM	Personal Wellness Manager
QoS	Quality of Service
RF	Radio Frequency
RFID	Radio Frequency Identification
RSS	Received Signal Strength
RSSI	Received Signal Strength Indicator
SD	Secure Digital
SMAC	Sensor Medium Access Control
SMS	Short Message Service
SNR	Signal-to-Noise Ratio
SPIE	Sensing and Perceptual Intelligence/Emulator
SQCIF	Sub-Quarter Common Interchange Format
UHF	Ultra High Frequency
VSN	Video Sensor Network
W2SU	Wearable Wireless Sensors Unit
WAN	Wide Area Network
WeCare	Wireless Enhanced Healthcare
WiMAX	Worldwide Interoperability for Microwave Access
WISP	Wireless Identification and Sensing Project
WLAN	Wireless Local Area Network
WSN	Wireless Sensor Network
ZUPS	ZigBee and Ultrasound Based Positioning System

1. INTRODUCTION

Wireless Sensor Network (WSN) 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 [1]. 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 [2]. 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 [3] forecasts that in the next 20 years, the 65-and-over population in the developed countries will be nearly 20 per cent 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 [4]. One promising application in that area is the integration of sensing and consumer electronics technologies which would allow people to be constantly monitored [5–7]. 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 [8, 9]. 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 [10]. 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.

The importance of integrating large-scale wireless telecommunication technologies such as Global System for Mobile Communications (GSM), Wi-Fi Mesh (IEEE 802.11s), and Worldwide Interoperability for Microwave Access (WiMAX), with telemedicine has already been addressed by many researchers. Further improvements will be achieved by the coexistence of small-scale personal area technologies like Radio Frequency Identification (RFID), Bluetooth (IEEE 802.15.1), ZigBee (IEEE 802.15.4), and wireless sensor networks, together with large-scale wireless networks to provide context-aware applications [11]. 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, that 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.

In this thesis, we propose an architecture for an intelligent healthcare monitoring system that integrates not only different sensing modalities but also several large scale networking technologies like the Internet and GSM in order to deliver a seamless healthcare monitoring service for especially the elderly and the children. We also built *Wireless Enhanced Healthcare (WeCare)* testbed using the proposed architecture and evaluated its applicability. In the testbed implementation, we build a small house with three rooms in a $55m^2$ laboratory room. The emplaced wireless sensors and wireless IP cameras and active RFID tags enable us to remotely monitor the house at any time. Moreover, with preconfigured alarm definitions, the system is also capable of identifying odd conditions in the house and produce GSM Short Message Service (SMS) messages and e-mail notifications for the caregivers. In this way, WeCare enables elderly people with cognitive or physiological disabilities to survive an independent life while enjoying the comfort of continuous monitoring against emergency situations. WeCare also helps parents both of which have to work during long hours. At any time and place, they can monitor their homes through live video. The user-defined alarm generation mechanism enables them to personalize the events they want to be notified about. For example, the baby's being awake between $14:00-16:00$ hours during the day or the baby's sleeping all day may indicate some problems for some parents while others may be worried about the caregivers' watching too much television and not caring about the child. Finally, WeCare can also be used for house monitoring when nobody is present with the help of embedded wireless sensors. The fire or burglar alarms may be set for such monitoring.

While continuous in-house monitoring will pose many benefits on futuristic health-care monitoring scenarios, there are cases where indoor monitoring is not sufficient. When the elderly who are susceptible to sudden falls or the patients recovering from an operation in a nursing home or hospital are considered, the continuous monitoring in indoor places will not be sufficient for surviving an independent life. They should be able to move around the nursing home's or hospital's garden freely while being monitored. However, setting up a monitoring environment for outdoors is not easy and sometimes impossible. Wireless sensor networks can also be the remedy in that case. With the advances in Complementary Metal Oxide Semiconductor (CMOS) cameras and availability of low-cost hardware have led to the emergence of Video Sensor Networks (VSNs). These camera-equipped sensors are capable of generating and relaying video streams. Generally, VSNs operate in an event-triggered mode. Nodes start producing video frames as soon as they detect a target within the sensing radius and the Field of View (FoV) and continue producing video frames as long as the target is within the range as shown in Figure 1.1. The number of frames produced is a function of the target residence time inside the coverage area and the camera frame rate. The residence time depends on the target speed, V, and the path length, D_{AB}, covered inside the FoV.

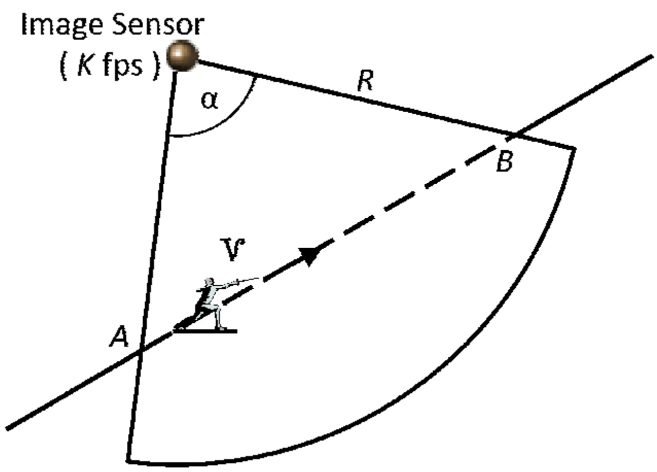


Figure 1.1. Representation of video sensor nodes' event detection

The increased traffic volume in VSNs pose significant challenges for successful arrival of the video frames at the sink. During wireless communication, environmental noise and packet collisions lead to packet errors frequently. In critical applications such as healthcare monitoring, these challenges must be addressed carefully. The successful arrival of most of the frames and within a tolerable amount of latency are the main issues for such applications. On the other hand, VSNs for healthcare monitoring are intended to track and monitor only the targeted patients or residents within the surveillance area. Therefore, the traffic caused by other people, animals or objects moving in the same area should be suppressed. We propose the use of small inexpensive RFID tags for this purpose. This is accomplished via enhancing the triggering mechanism of video sensor nodes with RFID readers as in the case of SkyeRead M1-Mini [12] which is a low-profile RFID device that reads and writes industry standard $13.56MHz$ RFID tags. This RFID reader can also be connected to Crossbow's MICA2DOT mote [13]. With the use of similar technology VSNs can be improved so that they only produce frames only for the intended targets.

RFID is a very mature technology and has been used in many areas such as electronic article surveillance,access control and inventory tracking systems. An RFID system has two components an RFID reader and an RFID tag. The RFID reader is the transmitter that uses an external power source to generate the signal that activates the reader's antenna and creates the appropriate radio wave. When this radio received by an RFID tag, some of the energy is reflected by the tag in a particular way depending on the identity of the tag. The RFID reader also acts as a radio receiver, so that it can detect and decode the reflected signal in order to identify the tag. An RFID system is asymmetric, i.e., the reader is big, expensive and power consuming whereas the RFID tag is small, inexpensive and can be activated by small power [14].

The RFID technologies can be classified according to the tags' operation in the following way:

- Passive tag RFID systems do not require any power source at the tag. The tag uses the energy of the radio wave to power its operation. This results in the lowest tag cost, but at the expense of performance.
- Semi-passive tag RFID systems use a battery in order to achieve better perfor-

mance in terms of operating range. The battery is used for operating the internal circuitry of the tag during communication, but is not used to generate radio waves.

- Active tag systems use batteries for their entire operation, and can therefore generate radio waves proactively, even in the absence of an RFID reader.

The RFIDs can also be grouped according to their operating principals [15].

- Near-field RFID : works by induction at Low Frequency (LF) and High Frequency (HF) bands. This is the most widely used approach for implementing a passive RFID system.
- Far-field RFID : They operate in the Ultra High Frequency (UHF) and microwaves frequency bands. They make use of propagating electromagnetic waves for operation. A typical far-field reader can successfully interrogate tags three meters away

In our outdoor monitoring application, an active RFID system operating in the UHF range will provide the necessary function. Additionally, RFID and sensor hardware convergence, which has already been realized in end-products [16, 17], enables the use of RFID enabled sensors. When VSNs are improved with these additional sensing mechanisms, not only video frames but also physiological information will be of much importance. Furthermore, with the help of extra sensors, the emergency situations such as high blood pressure or high body temperature can be sensed and reported together with the video frames as in the case of indoor monitoring. These frames also contain life-critical information, therefore, we propose an emergency based queueing mechanism for the emergency video frames in multi-hop VSNs. With this feature, the video frames that contain emergency situation identifier are given priority over those that are not emergent. The video frames containing healthcare information help identifying the situation better and taking the required actions quickly.

Without VSNs, the realization of this outdoor healthcare monitoring scenario would only be possible under the supervision healthcare professionals. However, this would be an infeasible solution for large amount of residents. VSNs for outdoor healthcare monitoring then can be used in conjunction with the supervision of healthcare professionals for further improving the performance of the healthcare monitoring system. The main motivation behind this scheme is to provide the optimal use of the scarce resources like healthcare professionals and network bandwidth.

The organization of this theses is as follows: In the second section of the thesis, we present the key issues that must be taken into consideration while designing pervasive healthcare monitoring systems, provide a detailed literature survey on the existing healthcare monitoring applications using WSNs and RFID. We also discuss benefits of these pervasive healthcare monitoring systems and design challenges. The third section is dedicated to the architecture and design description and implementation details of WeCare. In the fourth section, we extend the indoor healthcare monitoring system to the outdoors. We evaluate the performance of VSNs using RFID for healthcare monitoring in a nursing home or hospital garden setting by Operations Network (OPNET) simulations. The traffic load reduction by using RFID is proposed and evaluated. We also propose emergency frame based queueing for VSNs and explore the ways of further improving the performance of VSNs for efficient healthcare monitoring with the reduced number of healthcare professionals. In the last section, the conclusions are presented and some future works on the thesis is suggested.

2. WIRELESS SENSOR AND RFID NETWORKS FOR HEALTHCARE

2.1. Key Issues 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 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 Figure 2.1. Based on this observation, in a typical scenario, there are four different categories of actors.

- 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.
- 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

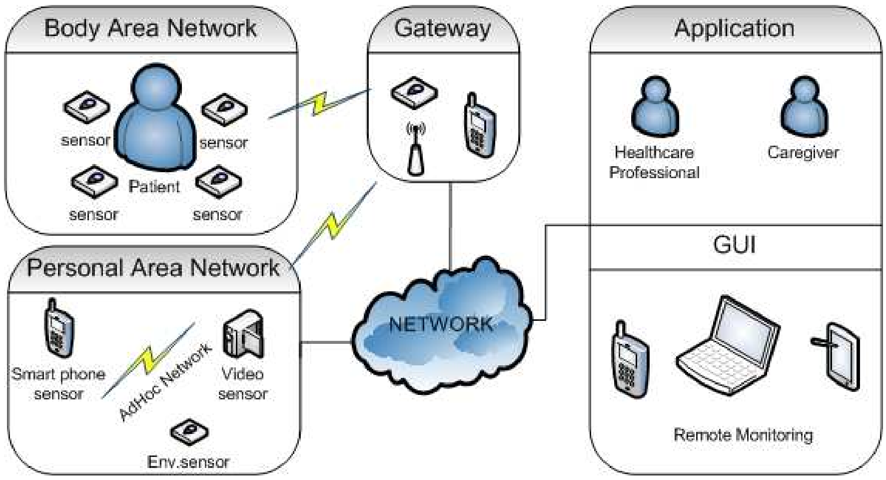


Figure 2.1. Overview of a simple WSN application scenario for healthcare

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 2.1, the key issues of these subsystems are provided.

2.1.1. 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

Table 2.1. The key issues of pervasive healthcare monitoring systems

Subsystem	**Issue**
Body Area Network Subsystem	Power consumption
	Transmission power of the sensors
	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 and privacy
	Congestion prevention
Wide Area Networks	Data rate
	Reliable communication protocols
End-user healthcare monitoring application	Security and privacy
	Reliability
	User-friendliness
	Middleware design
	Scalability and interoperability
	Context-awareness

of energy efficient Medium Access Control (MAC) protocols and energy efficient sensor devices are critical [18]. The study in [19] has shown that the technologies like Bluetooth and Wi-Fi (Wireless Fidelity) 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 ensure energy efficiency [20, 21]. Moreover, by using very low power Pyroelectric Infra Red (PIR) sensors as in [22], a simple yet efficient remote monitoring application can be developed.

Another important issue is the output transmission power of the sensors. The output power must be kept minimal for health issues which may lead to coverage and communication problems. The study presented in [23] 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 and portability are other challenges 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 [24], which necessitates the integration of several network technologies like RFID and Near Field Communication (NFC) as proposed in [25]. In [26], 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 [27] also makes use of ZigBee and mobile phone for ECG and blood glucose measurement. In a similar study [28], 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 [29]. Nyan et al. have designed a wearable fall detection system that can detect the falls with an average lead-time of $700ms$ before the incident occurs, with no false alarms. Varshney [30] 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 [31], 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. There is also ongoing research effort on designing MAC schemes to meet the Quality of Service (QoS) requirements of emergency traffic [32].

Finally, security issues also need to be considered since the physiological data of the individuals is highly confidential. In [33], 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 [34], a secure key establishment and authentication algorithm is used for transmitting medical data from body sensors like ECG sensors to a handheld device of mobile patient.

2.1.2. 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 [35], 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 [36]. Efficient algorithms for locating RFID tagged objects through appropriate data collection and preventing data interference is needed.

The energy efficiency of the MAC layer is another important issue. In [37], 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 [38] 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 $25dB$ to $73dB$ when extraordinary ECG signal occurs.

The self-organization between the nodes are also essential. In miTag system [39], 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 [40], a self-organizing distributed scheme is proposed for recognition of the activities of the people.

2.1.3. Gateway to the Wide Area Networks

The gateway subsystem is responsible from connecting the BAN and PAN subsystems to the Wide Area Networks (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 [41], 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 [42], context-awareness provides the capability of selecting the suitable network interface for the data transfer.

Privacy and 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 [43]. The security scheme proposed in [44] 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 propose solutions to the man-in-the-middle attacks, session key and fake data injection.

2.1.4. 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 system 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 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 as large as the global scale. In Table 2.2 [45], the characteristics of the candidate wireless connectivity and mobile networking technologies are provided.

2.1.5. 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

Table 2.2. Wireless connection technology candidates for pervasive health systems

Technology	**Data rate**	**Cell Radius**
IEEE 802.11g/WiFi	$54Mbps$	$50-60m$
IEEE 802.11n/WiFi	$540Mbps$	$50-60m$
ETSI HiperLAN/2	$54Mbps$	$50-60m$
IEEE 802.16/WiMAX	$36-135Mbps$ for LOS, $75Mbps$ for NLOS	Up to $70-80km$
IEEE 802.16e/WiMAX	$30Mbps$	Up to $70-80km$
ETSI HiperACCESS	$25-100Mbps$	$1.8-2.5km$
ETSI HiperMAN	$25Mbps$	$2-4km$
WiBro	$18Mbps$	$1km$
HAP	Varies	Varies
IEEE 802.20	$16Mbps$	$> 15km$
IEEE 802.22	$18Mbps$	$40km$
Satellite (GEO)	Up to a few Gbps	Four satellites give global coverage
Satellite (MEO)	Up to a few Mbps	11 satellites give global coverage
Satellite (LEO)	Up to a few Mbps	Varies

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 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.

2.1.5.1. Security and privacy. Security and privacy must be ensured throughout the healthcare application scenario. Therefore, end-to-end security mechanisms are still needed. The application must guarantee a well defined degree of privacy with precisely formulated and verified rules [46]. The patients' health information must be assured to be viewed by the authorized parties.

2.1.5.2. Reliability. The application is also guaranteed to be reliable. In [47], 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. 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.

2.1.5.3. User-friendliness. As far as the healthcare applications considered, user friendliness cannot be overlooked. Casas et al. proposes user-modeling involvement to enhance the interaction in [48]. In [49], the authors are also concerned about the user-friendliness of the proposed system and surveyed it among a small elderly group and concluded that their interface should be revisited. The human 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.

2.1.5.4. Middleware design. The combination of sensors from different modalities and standards make it necessary to develop hardware independent software solutions for efficient application development [50, 51]. In this context, there are numerous studies focusing on the middleware design [52–54]. Middleware helps 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.

2.1.5.5. Scalability and interoperability. When the number of patients and caregivers increase, the scalable and easily deployable applications that can also support multiple receivers will attain much importance. 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 [55, 56].

2.1.5.6. Context-awareness. Context-awareness, defined as "providing relevant information and/or services to the user, where relevancy depends on the user's task [57]", is the core issue for smart home applications as well as remote health monitoring applications [58, 59]. Context-awareness can be provided through the use of different sensing modalities together while considering previously mentioned issues such as proper data aggregation and analysis. There are more ways for improving context information. In [60], 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 become easier. This semantic representation of wireless sensor networks data enables structured information to be interpreted more clearly. Also in [61], a similar ontology-based context model is employed. The study in [62], defines a service-oriented ontology for wireless sensor networks. In a similar work [63], 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.

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 Figure 2.2. 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 help to activate the closest video sensor node to obtain the best scene about the event. This 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. 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.

2.2. Applications and 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 activities of daily living monitoring, location tracking, medication intake monitoring, medical status monitoring, and fall and movement detection. In the first category, the applications

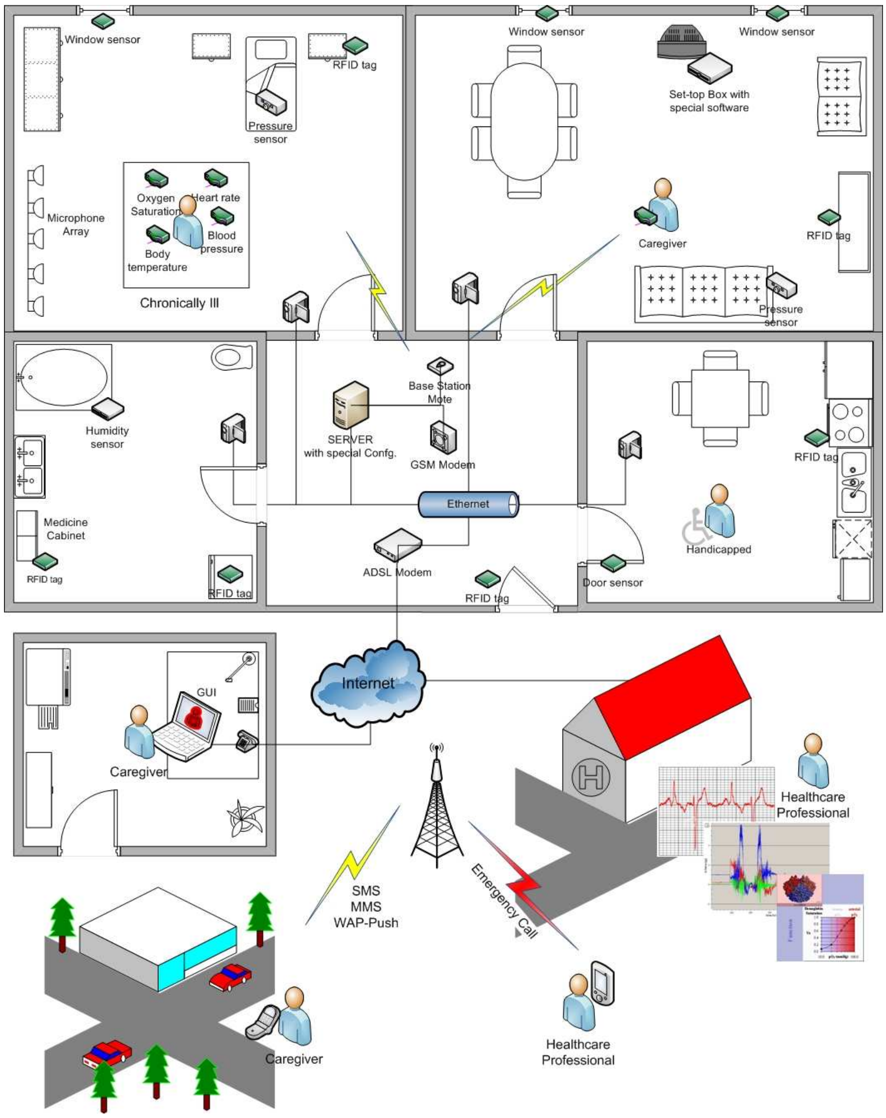


Figure 2.2. Future scenario for a seamless healthcare environment

try to identify and differentiate the everyday activities of the patients and the elderly such as watching television, sleeping, ironing, and be able to detect odd conditions. Location tracking and the medication intake reminder and monitoring systems can help cognitively impaired people to survive independently. Medical care applications make use of biosensors and environmental sensors in order to obtain comprehensive health status information of the patients, including ECG, heart rate, blood pressure, skin temperature, oxygen saturation. 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. In the following subsections we provide examples of applications belonging each category.

The research projects surveyed 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 a 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.

2.2.1. Activities of Daily Living Monitoring Applications

The Wireless Identification and Sensing Project (WISP) [64] 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 then 10 objects are actively used at any time.

The Caregiver's Assistant [65] 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. 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 trending information about what activities people are doing in the home.

The CareNet Display [66] is a digital Liquid Crystal Display (LCD) picture frame that has interactive features. 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. After configuring the system, the caregiver can monitor the daily activities or medication instantly. The five-day trend views for the events are also available.

The LiveNet [67] is a real-time distributed mobile platform. The system has three components: a mobile wearable PDA platform based on the MIThril architecture [68], a software architecture that allows the creation of distributed applications using context information, and a real-time context engine used for implementing lightweight 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 [69]. In [70], machine learning techniques are employed for categorizing the abnormal human activity based on body worn sensors data.

The work presented in [71] combines the data from RFID tag readers and accelerometers in order to classify the activities of daily living. Classifying activities of daily living by using only RFID technology requires a large number of RFID tags to be placed on the objects. Likewise, by using only accelerometers, there should be several sensors placed on body locations such as wrist, hip, and thigh. In this work, a single three-axes accelerometer worn on the wrist is used and reducing the number of RFID tags did not affect the results significantly.

The authors in [72], conduct experiments on 104 hours of activity data collected from a person living in a home 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. The authors conclude that the activities like "eating" and "reading" were difficult to detect and they require the use of additional sensors and improved algorithms.

2.2.2. Location Tracking Applications

ALMAS [73] 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 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.

Chang et al. [74] propose an RFID based way finding system for cognitively impaired patients is presented. Passive RFID tags are placed in important locations where patients need to make decisions about the next action to take, such as turning right or left. Patients 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. A tracking function is present where the visited positions are tracked and logged and in case of anomalies, alarms are raised.

ZUPS is a ZigBee and ultrasound based positioning system (ZUPS) that provides multi-cell coverage [75]. ZigBee is preferred because of inter-operability 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.

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 is proposed in [76]. 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.

2.2.3. Medication Intake Monitoring Applications

The prototype described in [77] aims 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 [78] 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.

Three applications are presented in [79]. Mobile Patient Caregiver Assistant (mPCA) is designed specifically for patients with Alzheimer's Disease (AD) and it is activated when the patient need to do a particular activity. After the attention is captured by using the closest monitor according to the patient's location, the system delivers the task to be done by the elder by playing a video clip. The ultrasonic location determination is used to follow the orientation of the patient, and to subsequently select an ideal monitor to play the video clip. If the task can not be delivered because the elder does not respond or the elder asks for help, the system makes use of tracking cameras to take a recent picture of the elder. This picture is sent to the phone of the caregiver. General Reminder System (GRS) reminds the elder to perform critical tasks such as medication intake and doctor appointments. It makes sure the elder takes medicine doses according to the schedule to ensure the medicine works effectively and the illness is properly treated. This application plays an audio message on the elder's smart phone whenever a medicine is due. Then the patient uses the mobile scanner attached to the phone to check if it is the right medication or not. The smart phone sends the data read by the scanner to the server, which checks how much medicine is available to order a refill whenever the quantity goes below a certain level. Augmented Awareness System (AAS) enhances the level of awareness of the occupants by notifying them when certain events happen and also reduce the level of efforts by automating tasks (e.g. controlling appliances and doors).

2.2.4. Medical Status Monitoring Applications

MobiHealth [80] 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.

AlarmNet [81] is a wireless medical sensor network system prototype that has five components. The mobile body sensor network is responsible for the physiological monitoring and the location tracking functions. The emplaced sensor network provides a spatial context and environmental information such as temperature, motion, humidity. The AlarmGate connects the wireless sensor and IP networks and also responsible for privacy, power management, query management, and security. The back-end database stores the data for long-term analysis and mining. The user interface allows caregivers to query sensor data through the AlarmGate to satisfy the privacy constraints.

Several prototypes are presented by a group of researchers in [82]. 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 will alert the caregiver about the firefighter's health status. Heart@Home is another similar prototype blood pressure monitor for home use. A mote is placed inside the wrist cuff connected to the electronic pressure sensor which computes the patient's blood pressure and heart rate using the oscillometric method. The mote then timestamps and broadcasts the readings. The base station plugged into the user's computer records these messages and provides a graphical representation of the patient's blood pressure and pulse rate over time. The final example, 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.

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 in [41]. 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. In [83] an adaptive algorithm for computing the heart rate and its variance from ECG data is proposed for a similar wearable ECG system.

Mobile ECG [84] is an 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 analyses 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 [85].

CodeBlue [86] is a hardware and software platform developed at Harvard University. The hardware design part includes the design and development of a 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. It also integrates a localization system called MoteTrack [87]. It is an RF-based localization system used for locating the patients and healthcare professionals. The caregivers are able to access the patients' information in real-time via mobile devices like PDAs, Laptop computers.

The LifeGuard [88], 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, blood pressure. The sensor data are collected and stored by a wearable device called Crew Physiological Observation Device (CPOD). It has three-axis accelerometers and skin temperature sensors internally. The base station part is a Bluetooth capable tablet computer. It can display and also store the data streaming from CPOD for further evaluation.

The Baby Glove [82] 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 vitals 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.

Physical Activities Healthcare System (PATHS) [89] includes a wearable wireless sensors 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.

Zhou et al. propose a three layer network structure for a pervasive medical supervision system based on wireless sensor networks [90]. The first layer is the biosensor layer providing information such as the oximetry, the heart rate/pulse and the blood pressure. The biosensors 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 privacy and security issues are left as a future work.

AWARENESS [91] is a smart context-aware health application. 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. 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 can not 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.

Mobile Agent Electronic Triage Tag System (MAETTS) [92] is based on a MANET of mobile agents which can used in emergency situations. When a patient is observed to be in an emergency situation, his or her information is transferred by a mobile agent which hops from one handheld device to the other within the MANET. RFID tags are used to identify the patients, and their geographical position is obtained by GPS. The main advantages of the system is that it does not require any network infrastructure. The reliable transportation of the information is asynchronous, and a permanent connection with all devices of the system is not required.

Lin et al. present a system infrastructure using ubiquitous network composed of Wireless Local Area Network (WLAN) and cable television (CATV) network serving as a platform for monitoring physiological signals including heart rate, blood pressure, and body temperature anytime either at home or at frequently visited public places [93]. The system can classify the health levels of the patient as “normal”, “remind”, or “recommend for revisiting” according to the variation of physiological signal and transmit the information to the patient or the caregivers. Personal Wellness Manager (PWM) [94] is another continuous activity monitoring application with a wrist-worn device to provide immediate feedback on daily activity like sleep and physical activity.

2.2.5. Fall and Movement Detection Applications

The Ultra Badge System [95] is a three dimensional tag system designed to realize the sequence of the accidental events such as falls of the elderly people and avoid them by alerting the caregivers beforehand. The Ultra Badge System consists of ultrasonic receivers embedded in the environment and wireless ultrasonic emitters placed on objects. 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.

A human activity monitor and fall detection system is presented in [96]. The system uses only a three-axes accelerometer to identify human activities. The system consists of two sensor nodes and a signal processing software. 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 high as 81 per cent correct detection of a fall while running and resting when the mote is worn on the chest rather than on the wrist.

A prototype for remote healthcare monitoring is presented in [97]. It consists of a smart phone application and a server located at the healthcare center. The smart phone application processes the data coming from the accelerometer locally to reduce the communication overhead, and communicates with the server at home over a wireless channel or a cable connection. The home server controls the web cameras and it is also responsible from the information exchange with the healthcare server over an Asymmetric Digital Subscriber Line (ADSL) connection. The prototype system is capable of sensing falls in the following way: After a large acceleration, the user’s position is analyzed and a fall is decided when the user’s position is horizontal after some period of inactivity.

The Information Technology for Assisted Living at Home (ITALH) [98] 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.

Smart Home Care Network [99] is a multi-modal home-based monitoring application. The sensor network contains a user badge node with accelerometers and voice transmission over IEEE 802.15.4 capability, 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 connects the user badge to the phone network via IEEE 802.15.4 radio link allowing the two way interaction.

HipGuard [100] 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. 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 [101], a more obtrusive system which consists of seven sensor units each has a three-axes acceleration sensor and three gyro sensors aligned on three axes, is proposed for gait analysis.

2.3. Benefits and Challenges of the WSN Solutions for Healthcare

In this section, we present the benefits achieved with the pervasive healthcare systems and challenges observed while designing such systems. The stated challenges must be studied for fully enjoying the benefits of such systems. Moreover, there are trade-offs that must be taken into account for the design and development of pervasive healthcare systems. These trade-offs require detailed exploration.

2.3.1. Benefits

<u>2.3.1.1. Remote monitoring.</u> 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 [10] will be enabled to have a more independent and easy life. The little children and babies will also be taken after in a more secure way while their parents are away. The special caregivers dependability will be decreased.

<u>2.3.1.2. Context-awareness.</u> 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 achieved mostly by multi-modal sensing helps identifying the unusual patterns. Since there are more types of sensing modalities in multi-modal systems, the context-awareness is relatively high. AWARENESS [91] and CareNet Display [66] are highly context-aware solutions. The Smart Home Care Network [99] and ITALH [98] systems understand emergency situations like falls and trigger intelligent actions such as making an emergency call to a medical center enjoying the integration of the sensor network with other public networks.

<u>2.3.1.3. Real-time Event Triggering.</u> In healthcare applications, a real-time system is actually a soft real-time system, in which some latency is allowed. 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.

2.3.1.4. Reduced Costs. 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 [65], 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.

2.3.2. Challenges

2.3.2.1. Unobtrusiveness. The design and development of wearable sensor platforms without violating unobtrusiveness is still a significant challenge for most researchers, however, with the use of small RFID and ultrasonic tags or video sensor nodes, this challenge can become a benefit as in UltraBadge [95], WISP [64], and mPCA [79]. When the patients have to carry sensors attached on their bodies as fall detection systems described in [96] and FireLine [82], unobtrusiveness become a major challenge. The need for integrating different sensors into one solution makes it harder as in the sensor units of LiveNet [67] and PATHS [89].

2.3.2.2. Lifetime. The power efficient mechanisms are needed to be developed as in AlarmNet [81] because the increased number of sensors brings power and lifetime challenges within. In WISP [64] project, the battery-free RFID tags are very power efficient whereas, in Mobile ECG [84] case, the ECG analyzer software running on the smart phone and the continuous Bluetooth communication between the sensor and the smart phone consume too much power posing a processing capability limit on the smart phone. With energy efficient routing protocols, the wireless communication channels will be used in a more appropriate way [20,21]. Moreover, using very low power sensors will provide power efficient solutions [22].

2.3.2.3. Security and Privacy. The security and privacy issues are left as future works in most of the studies; therefore, developing secure systems is still a challenge for such systems. There are also security and privacy issues on distributed systems like CodeBlue [86] which has an integrated location tracking feature and together with the private health information, the system's security mechanisms must ensure that the information is only retrieved by authorized parties.

2.3.2.4. Robustness. The main challenge for single-modal systems that only use a single type of sensors is robustness. The use of multi-modal systems helps improving robustness. LiveNet [67] and HipGuard [100] systems are examples of robust systems making use of multi-modal sensing. Moreover, these systems are more reliable in their measurements as in the case of the work presented in [71], which uses a combination of RFID tags and accelerometers to obtain better results for ADL classification.

2.3.3. Trade-offs

2.3.3.1. Coverage vs. Power Consumption. Since pervasive and ubiquitous remote monitoring applications for healthcare monitoring are needed to be developed, the wide coverage range is essential. However, the increased coverage will bring power consumption challenges within. With the intelligent and power efficient routing schemes, the increased coverage can be attained without increasing the output power. Multi-hop and ad-hoc architectures may be a remedy in that case.

2.3.3.2. Unobtrusiveness vs. Accuracy. The sensor devices that must be carried by the users may cause comfortability problems. However, for the vital signs that are to be constantly monitored like ECG, blood pressure, etc. the sensors that are directly connected to the body yield more efficient results than environmental sensors like video cameras or than those that are integrated into clothing. The unobtrusiveness can not be fully achieved with the applications that need high degrees of accuracy. The solutions that provide the highest degree of unobtrusiveness without degrading the accuracy need to be developed.

2.3.3.3. Security vs. Availability. The security concerns of pervasive healthcare applications cannot be overlooked, however, when emergency situations occur these security requirements may pose significant difficulties on healthcare professionals. The trade-off between the security requirements and the intended functionality and availability of the application should be studied carefully.

2.4. Design Requirements

There are several design requirements for intelligent remote healthcare monitoring systems. To begin with, development of end-to-end healthcare applications is important. There are several prototypes mentioned in the previous sections, however, all of them focus on a particular problem such as fall detection or medication intake. These subset of functionalities should be integrated into one application for providing end-to-end, seamless healthcare monitoring applications. Since the previous research projects focus only on specific problems, the flexibility and ease of extendibility of these systems remain as open problems. Integration of new functionalities to these systems are limited and, in some cases, impossible. Most of the projects lack the graphical user interface part which is very important for all the actors in the system. Moreover, unobtrusiveness should be provided for the effective use of the healthcare monitoring system. The unobtrusive devices like video sensors should be used together with the wireless sensors for providing both unobtrusiveness and multi-modal sensing. Multi-modal sensing will improve the context-awareness of the system.

In order to provide the design requirements mentioned above, we built an end-to-end healthcare monitoring application, WeCare, that is capable of monitoring activities of the daily living, medication intake, medical status, location and able to identify sudden falls. WeCare system incorporates the functionalities of five groups of applications that exist in the literature. Besides, with the help of different sensing modalities like RFID, wireless sensors, and video sensors, WeCare system provides a highly context-aware solution for healthcare monitoring. The flexible alarm definition mechanism helps identifying many different alarm conditions that are determined by the users according to their needs. The addition of new types of sensors in the system is also very convenient. The configurations are handled via simple graphical user interfaces of WeCare. In the following chapter we provide the detailed system design of WeCare system.

3. WECARE SYSTEM DESIGN

WeCare is a wireless sensor network based application for remote healthcare monitoring of the elderly and the children especially. The multimodal sensing environment of WeCare provides a combination of different sensing modalities like video, RFID, biological and ambient sensing. The wireless sensors provide environmental context information like the ambient light and temperature. The RFID technology is used for location tracking and also as an input for activating the video sensors. In a seamless scenario, all sensor data is used to provide the context information which is forwarded to other nomadic and mobile actors such as caregivers, parents, and healthcare professionals over the Internet and GSM. The systems' basic functionalities are as follows:

- Incorporating different sensing modalities such as ambient light, temperature, sound, humidity and acceleration.
- Identifying the presence of the residents, i.e., which residents are at home.
- Identifying the location of the residents, i.e., in which room each resident is.
- Video broadcasting enhanced with location tracking.
- Providing web based remote access for the users.
- Providing e-mail and SMS notifications in emergency situations.
- Easy alarm setting via predefined alarm mechanisms.
- Flexible, personalized alarm definition via GUI.
- Alarm and event logging and archiving mechanism for later evaluation and monitoring.

We build the testbed for WeCare in a $55m^2$ laboratory. The testbed home consists of three rooms decorated as a living room, a bedroom and a kitchen. The picture of the testbed environment can be seen in Figure 3.1.

We have deployed several sensors in the environment. The hardware used in the testbed is listed as follows:

Figure 3.1. WeCare testbed rooms

- Living Room
  - One Crossbow IMOTE2 wireless mote with ITS400 sensor board – for temperature, humidity and light sensing
  - One GENETLAB SenseNode – for sound sensing
  - One AXIS 207W Network Camera
  - One UDEA RWID-R12 Active RFID Reader Antenna
- Bedroom
  - One Crossbow IMOTE2 wireless mote with ITS400 sensor board
  - One GENETLAB SenseNode
  - One AXIS 207W Network Camera
  - One UDEA RWID-R12 Active RFID Reader
- Kitchen
  - One Crossbow IMOTE2 wireless mote with ITS400 sensor board
  - One GENETLAB SenseNode
- Elderly
  - One Crossbow IMOTE2 wireless mote with ITS400 sensor board – for acceleration sensing
  - Two UTAG-12 Active RFID Tags
  - One Crossbow IMOTE2 wireless mote – as a base station

The system hardware components pictures are provided in Figure 3.2. The overall cost of these hardware equipments is around $3500.

Figure 3.2. WeCare hardware components

3.1. WeCare Architecture

The system architecture is composed of two main parts, one corresponds to the home environment and the other is at the healthcare control center for allowing remote evaluation. The architecture can be seen in Figure 3.3.

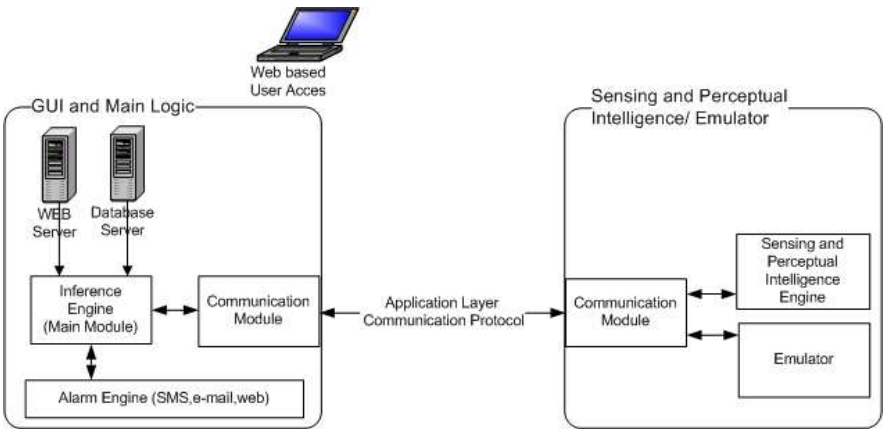


Figure 3.3. WeCare architecture

The "GUI and Main Logic (GML)" part of the architecture is responsible from

- Data aggregation,
- Data inference, and
- Data representation

Data is collected via the "Communication Module" and stored in the "Database Server". Deducing useful information from the collected data and making inferences according to the configured alarm definitions are handled by the "Inference Engine". When an alarm situation is observed, the "Alarm Engine" takes the required action such as sending SMS or e-mail notifications to the related users. The "Web Server" enables the remote monitoring via web-based "GUI". The users can access all the information about their homes at any time and place via web GUI.

In the "Sensing and Perceptual Intelligence/Emulator (SPIE)", the data is collected from the sensors deployed in the house by the "Sensing and Perceptual Intelligence Engine" and successful delivery to the GML module is handled by the "Communication Module". The communication modules in both parts of the architecture use a propriety "Application Layer Communication Protocol" for data exchange. The "Emulator" has been developed for testing purposes. It has the ability to pretend any kind of sensor data according to a specified distribution or a predefined pattern.

3.2. WeCare System Components

3.2.1. Graphical User Interface

We develop the graphical user interface by using Microsoft Silverlight for its support for animations, vectors and 3D graphics and video in web applications. Besides rich content, the web application is kept quite simple for user-friendliness. The web page has a navigation panel organized as a tree on the left and the multimedia content is displayed on the main screen. The page for the overview of the events in the house can be seen in Figure 3.4.

The object hierarchy starts with a "House" object. Each user in the system is associated with a single house. When the users login, they are directly taken to the home overview page they are associated with. The house object contains several "Room" and "People" objects. The Room objects have several "Sensor" objects and "Camera" objects associated with them, whereas People objects only have Sensor objects

Figure 3.4. WeCare home overview screen

associated. Additionally, each people has a default "Location" property which is of type "Room". The location of the people is identified by RSS of the RFID antennas deployed in the house. In this way, the camera associated with a person can also be identified and the stream from that camera is shown on the graphical user interface when the person is being monitored. Moreover, all camera streams are provided in a separate page for enabling the users for instantaneous monitoring of any room as shown in Figure 3.5.

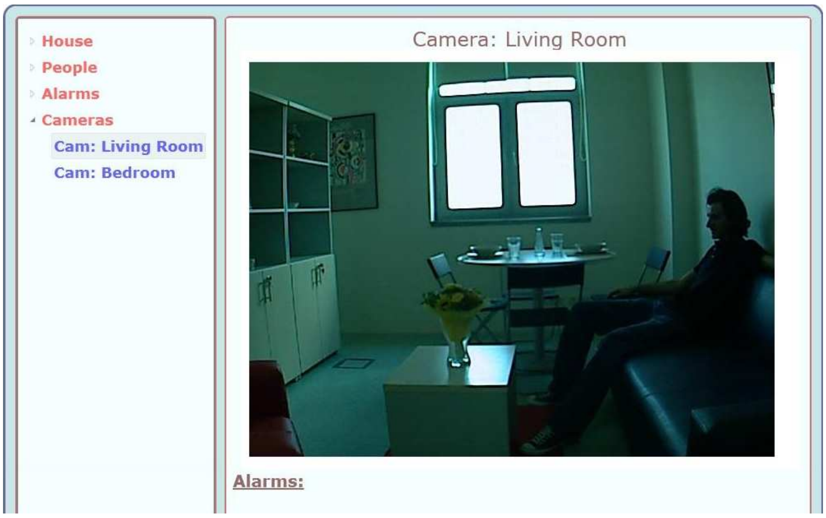


Figure 3.5. Living room camera screen

The sensor readings are grouped under associated room or people objects. The snapshot of the room is provided together with the instant sensor values, the generated alarms and the live camera view of the room as shown in Figure 3.6. The dynamic nature of this page allows updating the values and events on the page without any action from the user. Likewise, the sensors associated with the people are updated continuously and automatically. Besides, since the people objects are moving, the live camera view changes according to the location of the people being monitored. In this way, the person's presence and duration of his presence in the rooms can also be recorded by the system for later evaluation. This also helps identifying the activities of daily living pattern of the people and can be used to make inferences about the unusual occurrences.

Figure 3.6. Living room overview screen

A more detailed view of each sensor reading is also possible. When a specific sensor is selected to be monitored, the sensor readings are shown on a dynamic graph for identifying the changes in the sensor values visually. In Figure 3.7, the temperature sensors of the bedroom are being shown on the dynamic graph.

The alarms can either be configured by using predefined alarms like *the person has fallen* or *there is a fire in the room* as shown in Figure 3.8(a) or can be configured building more complex logical expressions regarding sensor readings. The "Alarm"

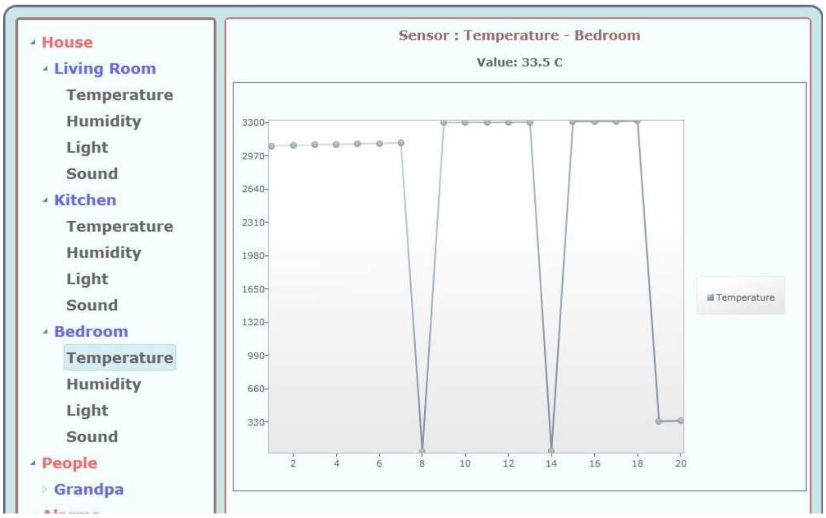
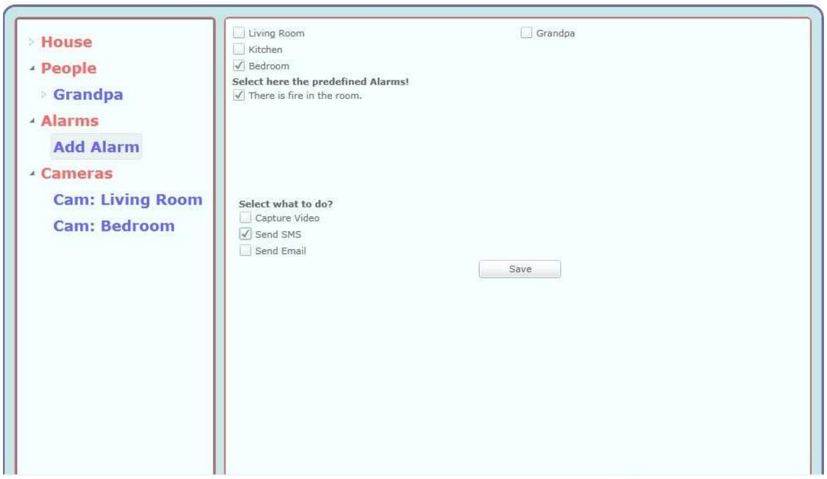


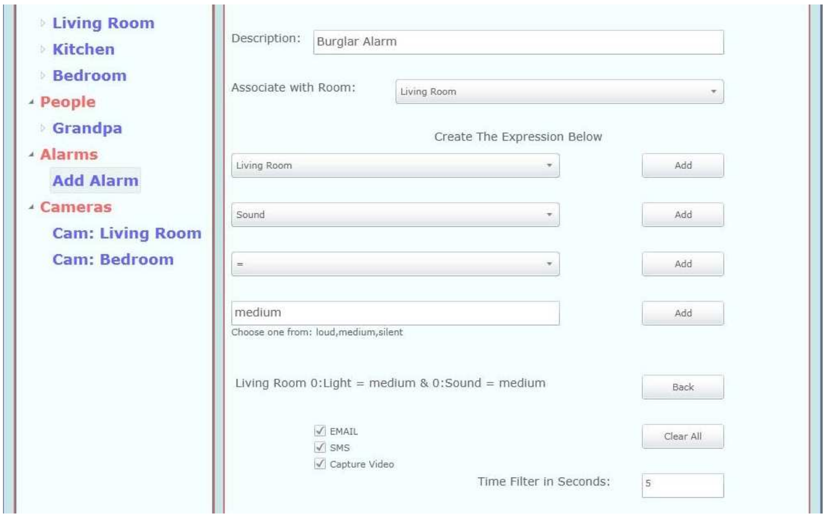
Figure 3.7. Bedroom temperature tracking screen

objects can be associated with a Room or People object or both. For example, an alarm expression like *the person fell down in bedroom and the bedroom is silent* can be defined for identifying a serious fall condition at which the person become unconscious. The user-generated alarm setting screen is shown in Figure 3.8(b). This flexible alarm setting mechanism also has a time filter for reducing the false alarm rate. This filter determines the duration of the alarm condition in seconds before raising that alarm and take the required actions. This timeout setting function helps eliminating the instantaneous sensor reading errors and other environmental conditions that may be interpreted as emergency conditions. Moreover, all the alarms can be configured to be active between specific time intervals and also according to the presence of the other residents in the house. For example, a fall alarm can be configured to be inactive when someone like a healthcare personnel is present in the house besides the person being monitored.

The generated alarms are logged after taking the emergency action such as sending SMS and e-mail. The users can view the alarm details on the graphical user interface as shown in Figure 3.9. The generated alarms are highlighted with red color. When the users handled the alarm situation they can change the status of the alarm to “Verified” or in case of false alarms the status can be changed to “False Alarm”. The



(a) Predefined



(b) User-generated

Figure 3.8. Alarm setting screens

false alarm feedback is important for the system for future calibration of the sensor devices and alarm conditions.

3.2.2. Main Logic

The Main Logic part of the system is composed of the "Inference Engine", the "Alarm Engine", and the "Communication Module". Communication Module is responsible for the data transfer between the healthcare control center ant the house being monitored. The communication is provided over socket based TCP/IP according to the propriety application level communication protocol. The alarm engine is responsible

Figure 3.9. Alarm view screen

for sending e-mails or SMS messages according to the alarm definitions provided by the Inference Engine. The Inference Engine is responsible from the data handling and manipulation. It behaves like an interface between the GUI and the database server, besides identifying the alarm conditions. The database access is provided by Windows Communication Foundation (WCF) services and LINQ to SQL classes. WCF provides the communication across components, applications, and systems. It was designed according to the service orientation mechanism. A service is a piece of code you interact with through messages. Services are passive. They wait for incoming messages before doing any work. Clients are the initiators. Clients send messages to services to request work. LINQ to SQL is a component of .NET Framework version 3.5 that provides a run-time infrastructure for managing relational data as objects. When the application runs, LINQ to SQL translates into SQL the language-integrated queries in the object model and sends them to the database for execution. When the database returns the results, LINQ to SQL translates them back to objects that we can work with.

The "Inference Engine" constantly checks for alarms by evaluating the alarm's conditions. It maintains the alarm start and end times with the algorithm represented in Table 3.1. The engine holds two database tables AlarmOn and AlarmOff for active and deactive alarms respectively, at a given time. AlarmList holds the alarm settings like the start and end times of the alarm checking and the timeout value for the alarms, that is the wait duration before switching to "Active" state when the alarm conditions occurred. When the handling mechanism identifies that an alarm has occurred, it puts a timestamp and waits for the timeout value before making that alarm active. When an alarm becomes active, alarm handling mechanism notifies the "Alarm Engine" for taking the required actions. Moreover, when an active alarm condition is no longer satisfied the handling mechanism timestamps the end time of that alarm and archives that alarm for later evaluation for the users.

3.2.3. Sensing and Perceptual Intelligence Engine

All sensor devices in the house are wirelessly connected to a base station mote which is connected to a computer located in the house. The XSniffer application installed on the base station mote, listens the radio and capture the data packets sent from other motes and forwards these packets to the USB port where it is connected to the computer. The SerialDump application in turn, collects the data packets from the port and forwards them to the "Sensing and Perceptual Intelligence Engine". The collected raw data are identified and classified according to the source node and source sensor type here and the values are converted to the interpretable values. Finally, the data strings are sent to the communication module for successful delivery to the healthcare center.

Since the data from the acceleration sensors are much frequent than other types of sensor data, the fall detection is handled in the "Sensing and Perceptual Intelligence Engine (SPIE)". In order to interpret the three-axes acceleration sensor data, the following window averaging method is used:

- Create a table that contains the last three values of the x, y and z axes.
- Every time new values arrive, the averages of the x, y and z axis acceleration values are calculated and compared with the new values.
- According to the difference values, the characterization of the motion is determined.

Acceleration values can take values between $-6g$ and $+6g$. With the calibration experiments, we observed that the difference value is below $1.5g$ when there is not too much motion. If the sensor is moving constantly or turning around, the difference value exceeds $1.5g$ slightly. If we shake the sensor or it falls, the difference value usually takes values between $2.5g$ and $6.0g$. According to these observations, we fuzzily classified the movement of the object as “Normal”, “Fast” and “Extreme” respectively.

Likewise, RFID system works by interrogating the tags every second therefore, identification of the people’s location is handled by SPIE. With the RSS measurements obtained from the antennas of the RFID reader, the people’s locations are approximately guessed by the system. For calibrating the threshold values, we conducted several experiments. For eliminating the interference, we kept the output powers of the antennas as low as $-30dBm$. These low powers also provide a suitable radiation emission for an healthcare application.

3.2.4. Emulator

In order to test the system over more scenarios, we build an emulator that is capable of acting like any kind of sensors. The emulator software is also located at the home computer and able to produce sensor values according to a specific probability distribution or send specified values according to a predetermined scenario. In this way, the system can be tested against the probable future scenarios. The emulator is useful for discovering the effect of biological sensors such as ECG, blood pressure, glucose measurement sensors although they are not yet available, will appear soon.

With the emulator software GUI which is depicted in Figure 3.10, we are also able to control the sensors and the communication module settings. There are two types of objects: the real objects and the emulated objects. The real objects represent the real rooms, people and sensors in the house. The definitions and additions of new rooms, people and sensors are also managed here and sent to the control center via communication module. In this way, flexible definition of the organization in the house is achieved. We can easily configure the house settings when new sensors are available at the house, and new people are decided to be monitored. Besides, we can add or configure emulated objects for the rooms, people and the sensors that are not yet available. The communication module is capable of sending real data, emulated data and both emulated and real data at the same time. We can view the list of objects, the data types they produce and the explanations via the graphical user interface. For emulated data, we can specify the distribution of the randomly generated data or we can set a specific value to be produced by the emulator. For emulating time based attributes like the location of a person, we can make the emulator to send data according to a trace file. This enables us to implement any scenario in the testbed.

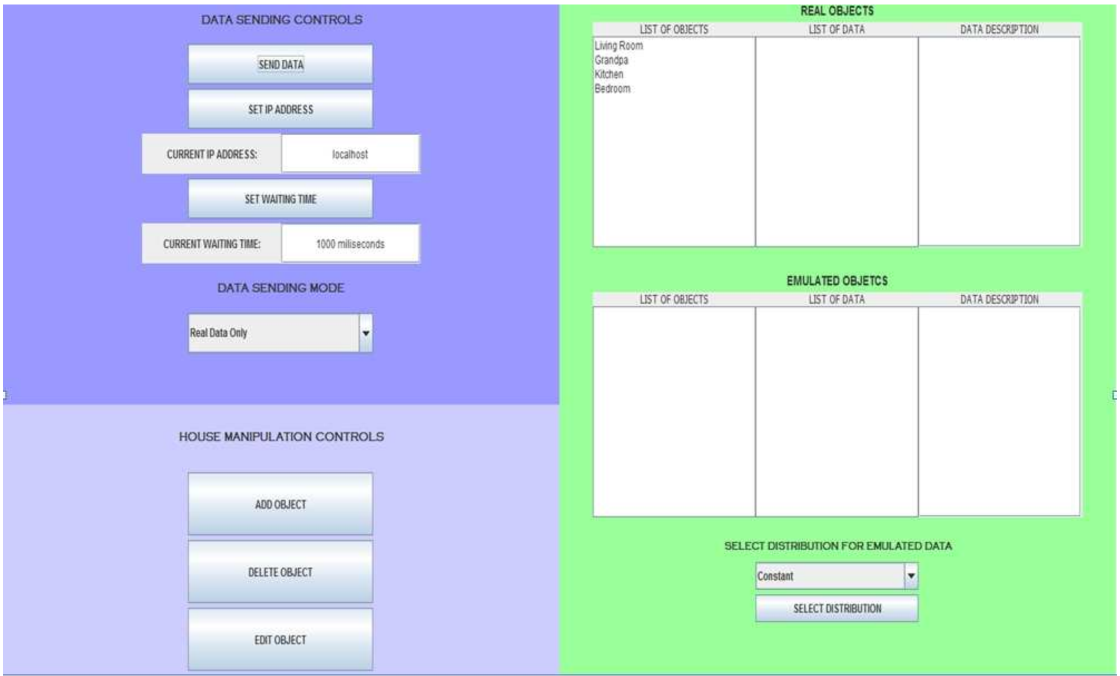


Figure 3.10. Sensing and Perceptual Intelligence Engine GUI

3.3. Evaluation of WeCare Sytem

We proposed an architecture for a remote healthcare monitoring system that incorporates different sensing modalities and communication technologies. We also developed the WeCare system for evaluating the applicability of the proposed architecture. We have deployed the sensors and the software we developed in a home-like testbed setting. We conducted several experiments for evaluating the testbed. The results indicate great potential for such multi-modal sensor systems to be used in healthcare monitoring applications for the elderly and child. Since indoor environments are convenient for wireless device communications in one-hop and broadband Internet access are available for almost everywhere, we do not have much difficulties in terms of deployment and communications. Therefore, we concentrated on the organization of the knowledge and calibrating the sensors which are of great importance for identifying the alarm conditions in a continuous healthcare monitoring application. On the other hand, when we intend to extend such a healthcare monitoring application to outdoors environment, we have significant difficulties with the deployment, maintenance and survival of the sensors. Because of this, we resort to the simulation technique for an outdoor scenario. In the following section, we represent the design and evaluation of an outdoor monitoring scenario.

Table 3.1. Alarm Handling Algorithm

Procedure for handling alarms

```
if alarmHappened = TRUE then
   if AlarmStatus.Time = null AND AlarmStatus.AlarmOnOff = 0 then
      AlarmStatus.Time ⇐ DateTime.Now
   else if AlarmStatus.Time <> null
   AND AlarmStatus.AlarmOnOff = 0
   AND DateTime.Now − AlarmStatus.Time > AlarmList.Timeout then
      AlarmStatus.AlarmOnOff ⇐ 1
      AlarmStatus.Time ⇐ null
      Insert into AlarmOn
      Check for alarm actions
   else if AlarmStatus.Time <> null
   AND AlarmStatus.AlarmOnOff = 1 then
      AlarmStatus.Time ⇐ null
   end if
else
   if AlarmStatus.Time = null AND AlarmStatus.AlarmOnOff = 1 then
      AlarmStatus.Time ⇐ DateTime.Now
   else if AlarmStatus.Time <> null
   AND AlarmStatus.AlarmOnOff = 1
   AND DateTime.Now − AlarmStatus.Time > AlarmList.Timeout then
      AlarmStatus.Time ⇐ null
      AlarmStatus.AlarmOnOff ⇐ 0
      Find the last occurrence of the alarm
      Insert into AlarmOff
   else if AlarmStatus.Time <> null
   AND AlarmStatus.AlarmOnOff = 0 then
      AlarmStatus.Time ⇐ null
   end if
end if
```

4. HEALTHCARE MONITORING WITH VIDEO SENSOR NETWORKS

In this chapter, an outdoor healthcare monitoring scenario in a nursing home or hospital with a garden is studied. The outdoor environments can be very hard for building an infrastructure based surveillance monitoring system. The cabling costs and other deployment costs can be problematic in some cases. VSNs can be a remedy for such cases, since the deployment and cabling costs are diminished. Besides these advantages, there exists some drawbacks with VSNs such as the battery life. The energy is the most scarce resource for VSNs and it is directly related to the network lifetime. Because of this, there exist significant research effort for rechargeable sensor networks that are aimed to be deployed in habitat monitoring. As the technology evolves, the VSNs with solar cells will be commercially available for most users [102].

Since designing a practical experiment outdoors is extremely difficult, we explore the applicability of VSNs through simulations for an outdoor healthcare monitoring for the scenario depicted in Figure 4.1. We also propose the use of the RFID tags for efficient use of the bandwidth and reduced number of healthcare professionals for further improvements.

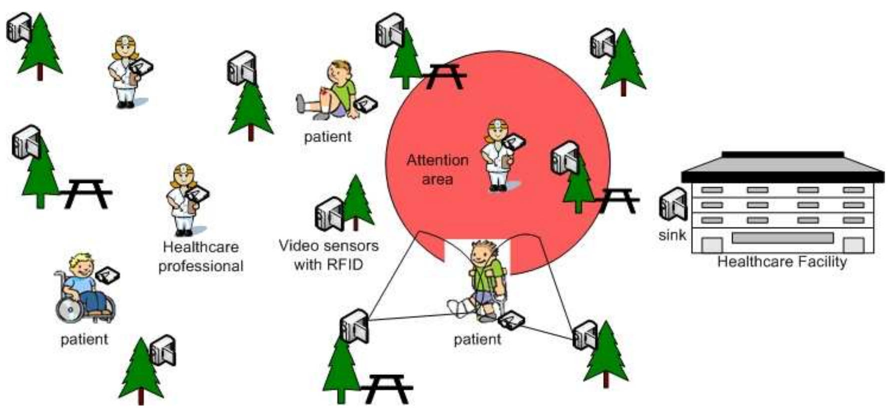


Figure 4.1. A healthcare facility with a garden

4.1. System Model

We use the OPNET simulation environment for the performance tests. We have used the SMAC [103] and GPSR [104] protocols as the underlying MAC and routing protocols, respectively. The sink is placed at the middle of one side of the surveillance area where the sensor nodes are deployed uniformly in a random fashion. All the nodes are capable of taking images and compressing them with the cameras integrated on their hardware. Since the size of the data transmitted is directly related to the size of the image, SQCIF (128×96 pixel size) format is assumed. The image module employs intra-frame encoding which results in compressed images of size $10kbits$. We apply the JPEG compression which is assumed to be available on the image module.

Sensor nodes are designed to dynamically power up and down the equipments to save energy. Especially the antenna part of the devices changes its power state in duty cycles (DC). Sensor nodes are expected to agree upon the duty cycle strategy and keep on networking without large amounts of information losses. We use 10 per cent DC in our simulations. The buffer size at the sensor nodes is selected to be $200kbits$, therefore each sensor node can have 20 frames in its buffer before sending them. The excess amount of the frames are dropped immediately.

The software controlled frame rate feature allows capturing the video with rates one to eight frames per second (fps). Event triggered data generation is simulated where the triggering event is the visual detection of a patient. Since the cameras support background subtraction feature, they only produce an image when the scene changes significantly. Hence triggering occurs when the patient is within the camera detection range of $30m$ and is within the Field of View (FoV) of 52 degrees. The patient is assumed to move in the surveillance area according to the Random Waypoint Mobility Model where the patient speed is one meter per second and the pause time is set to zero seconds. The simulation parameters are summarized in Table 4.1.

We designed experiments for exploring the effects of the bandwidth, camera frame rate and the number of the patients. The investigated factor values are provided in

Table 4.1. Simulation Parameters

Parameter	**Value**
Surveillance area	$200 \times 100m$
Number of sensors	40 nodes
Deployment type	Uniform random
Video frame size	$10kbits$
Packet size	$1kbit$
Buffer size	$200kbits$
Camera detection range	$30m$
Communication range	$40m$
Field of view	52 degrees
Patient mobility model	Random Waypoint
Duty Cycle	10 per cent
Speed of the patients	$1m/s$
Routing	GPSR
MAC	SMAC

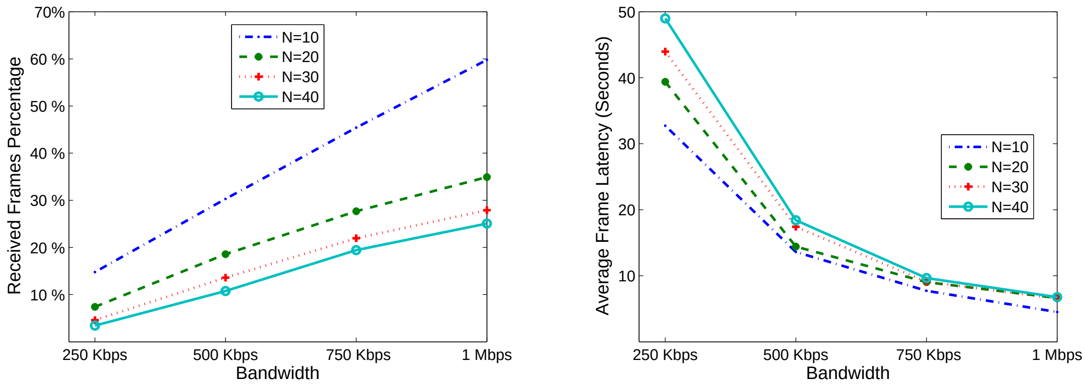
Table 4.2. Each simulation is repeated five times for reducing the experimental errors. For each set, we simulated one hour of network operation where the statistics of the first 30 minutes is discarded for a better steady state analysis. In order to assess the effects of the factors, we use the performance metrics as the percentage of the received frames at the sink per second and the average frame latency in seconds.

Table 4.2. Investigated Factors

Factor	**Values**
Bandwidth	$250kbps, 500kbps, 750kbps, 1mbps$
Camera frame rate	$1, 2, 4, 8fps$
Number of the patients	$10, 20, 30, 40$

4.2. Simulation Results

Simulation results represented in Figure 4.2 show that with a 250$kbps$ bandwidth, the percentage of the received frames is below 10 per cent when the number of the patients exceeds 10. We can conclude that for receiving a reasonable amount of the frames at the sink, we need higher bandwidths. The percentage of the received frames with 10 patients in the surveillance area shows a linear increase while for 20, 30, and 40 patients the increase in the received frames is not as high as in the 10 patient case. This suggests that the number of the patients in the surveillance area should be low, however, it is unlikely that a nursing home or hospital will have less than 10 patients moving around. Therefore, we need improvements other than higher bandwidths for such a scenario. As far as the latency of the frames are considered, which is also important for healthcare monitoring, again we have difficulties at lower bandwidths. The 250$kbps$ bandwidth can only provide latencies above 30 seconds and up to 50 seconds for 40 patients, although the successful frame arrival rates are very low. The average frame latency falls below 20 seconds with 500$kbps$, and 750$kbps$ and one mbps bandwidths provide nearly 10 seconds of frame latency with a four frames per seconds camera frame rate as shown in Figure 4.2(b).

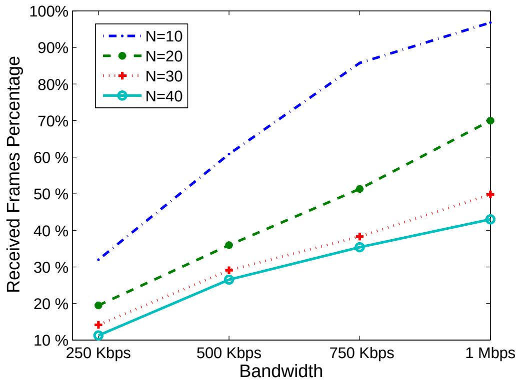


(a) Percentages of the received frames

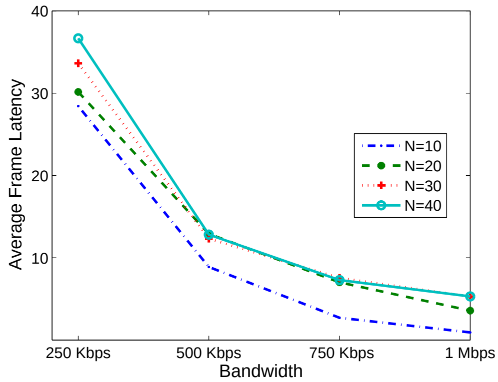
(b) Average Frame Latency

Figure 4.2. Simulation results with four fps camera frame rate

With lower camera frame rates such as two fps, we obtain better results both in terms of the percentage of the received frames and the average latency as represented in Figure 4.3(a) and 4.3(b) respectively. The halved camera frame rate with higher bandwidths like $750kbps$ and one mbps provides nearly real-time monitoring for 10 patients, with above 90 per cent frame arrival rate and below one second average latency, at the cost of reduced video quality. The increased number of the patients yields approximately 40 per cent of successful frame arrival with around five seconds of average frame latency.



(a) Percentages of the received frames



(b) Average Frame Latency

Figure 4.3. Simulation results with two fps camera frame rate

When we explored the dropped frames in detail, we observed that most of the frames are dropped at the source for lower bandwidths as shown in Figure 4.4. With $250kbps$ bandwidth, more than half of the camera frames are dropped at the node where they are generated. This implies that either we must have larger buffers at the sensor nodes or larger bandwidths. The larger buffers will not lead to decrease in the latencies therefore, obtaining larger bandwidths are essential. Semi-conductor manufacturers have begun producing transceivers that support data rates up to one mbps [105]. Hence, the next generation wireless sensors will be much more suitable for VSN healthcare applications.

4.3. Effect of RFID Usage

Since the large number of the patients degrades the performance of the network significantly at especially high camera frame rates, we proposed and tested the RFID triggered sensing mechanism. This is accomplished via enhancing the triggering mechanism of video sensor nodes with RFID readers. There are low-profile RFID devices

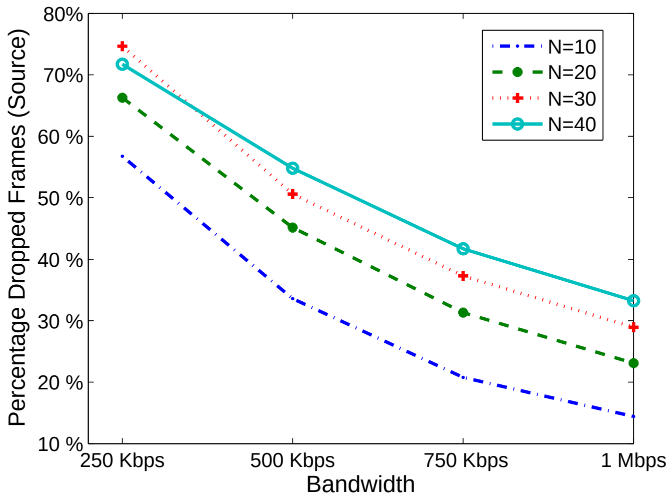


Figure 4.4. The percentages of the dropped frames at the source with four fps camera frame rate

like SkyeRead M1-Mini [12] that can also be connected to Crossbow's MICA2DOT mote [13]. By employing similar technology in VSNs, they are forced to produce frames only for the intended patients.

In the RFID enhanced scenario, the sensor nodes only produce frames when they identify the presence of the intended patients, who are wearing RFID tags. In this way, the extra traffic load arising from other people such as healthcare professionals or caregivers, relatives of the patients, gardeners and security guards, who are also moving around will not affect the network performance. In Table 4.3, we demonstrate the created frame reduction percentages for different proportions of decrease in the number of the patients. According to the simulation results that are mentioned in Section 4.2, the created frames are reduced 66.4 per cent with a 75 per cent decrease in the number of the patients. If only 25 per cent of the 40 patients were wearing RFID tags which identify them as critically ill people who need closer monitoring with the VSNs, the created video frames will be reduced 66.4 per cent. With one mbps bandwidth, the effect on the latencies are given in Table 4.4. The reduction in the average frame latency with a decrease in the number of the patients with the use of RFID tags, can go up to nearly 30 per cent.

Table 4.3. The reduction in the number of created frames with eight fps camera frame rate and one mbps bandwidth

		Number of Patients		
		10	**20**	**30**
Total Number of People	**40**	66.4%	36.0%	14.6%
	30	60.6%	25.0%	
	20	47.5%		

Table 4.4. Latency reduction with one mbps bandwidth and eight fps camera frame rate

		Number of Patients		
		10	**20**	**30**
Total Number of People	**40**	32.4%	17.4%	7.2%
	30	27.1%	10.9%	
	20	18.1%		

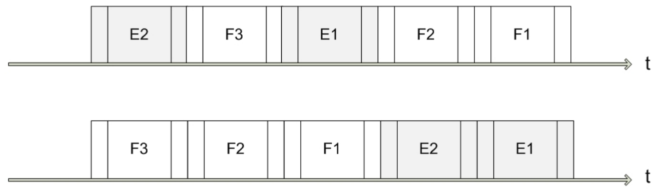
Besides providing performance increase by focusing only on the intended patients, the WSN and RFID integration that has already been realized in end-products will also be used for sensing purposes. These products will be widely used in the next generation WSNs. The concurrent use of the RFID and VSNs also moves us one step further in identifying the context of the sensed events. While monitoring with small video sensor nodes, the patient's posture and pose can be estimated with local image processing on the video sensor node. With this feature, we can identify some odd conditions like *patient has fallen down* or *patient is walking awkwardly*. However, the physiological emergency situations like *patient's body temperature goes up* or *patient is sweating too much* cannot be identified by image processing. The integrated RFID WSN sensing technology will be the solution to this fact. In such a scenario, VSNs will have to carry emergency information as well. In the following section, we purpose a new technique for handling the emergency situations in VSNs.

4.4. Emergency Frame Based Queueing

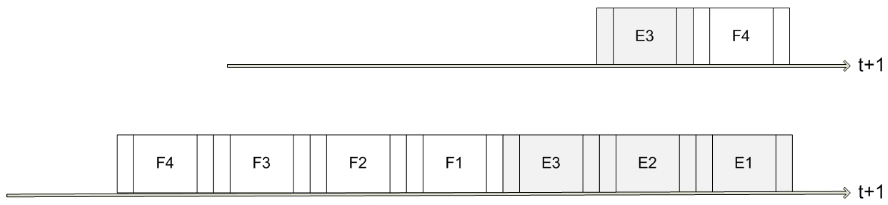
The concurrent use of RFID and VSNs and image processing help identifying the emergency situations such as high blood pressure, high body temperature and sudden falls. These relatively small yet life-critical data can be integrated in large video frames, making these frames the *emergency frames.* The emergency video frames containing healthcare information help identifying the situation better and taking the required actions quickly. Since these frames contain critical information, they must be assured to arrive at the sink. For this purpose, we propose an Emergency Frame Based Queueing (EFBQ) mechanism for improving the delivery of the emergency video frames in multi-hop VSNs. With this feature, the video frames that contain the emergency situation identifier are given priority over those that are not emergent.

In Figure 4.5(a), the frames arriving at a node at a given time t is represented. There are five frames two of which are the emergency frames namely, E1 and E2. Other frames F1, F2, and F3 are non-emergent video frames. Without EFBQ, these frames would be relayed in a First Come First Serve (FCFS) manner. Yet, with EFBQ the relaying order of these frames are changed according to their emergency flags and the time of arrivals as depicted. Suppose that before relaying any of these frames, two new frames one of which is the emergency frame arrived at the node as shown in Figure4.5(b). The new order of the relaying queue at time $t + 1$ is also presented. In this way, at any given time the emergency frames are given priority over non-emergent ones for assuring low latencies and higher arrival rates.

For emergency frame creation in our simulations, we preferred to use a random emergency frame generation with a probability of 10 per cent. Therefore, 10 per cent of the generated frames are randomly selected to be emergent frames. According to the new queueing mechanism, the emergency frame arrival rates are shown to be increased as depicted in Figure 4.6. For eight fps camera frame rate with one mbps bandwidth, the received frame percentage of all frames for 10 patients is a little above 30 per cent with the EFBQ. With the FCFS queueing, since the emergency frames are treated as any other frames, the percentage of the received frames are a little below 30 per cent.



(a) Queueing at the sensor node at time t



(b) Queueing at the sensor node at time $t + 1$

Figure 4.5. Emergency Frame Based Queueing

However, the emergency frame delivery ratio becomes nearly 85 per cent with EFBQ. Again, with the increased number of the patients, EFBQ enables us to deliver five times higher number of emergency frames to be delivered successfully.

4.5. Effect of The Proximity of Healthcare Professionals

We conducted several experiments on the capabilities of the VSNs for healthcare monitoring. The results exhibit that their capabilities are limited. Therefore, reducing the number of the frames carried by the network is the primary objective. For this reason, it is reasonable to accept that if a patient has already a healthcare professional nearby, he/she will not need additional attention from the VSN system. This fact can be used for further reducing the number of created frames in the system. Moreover, allowing a healthcare personnel for every single patient is not feasible. We propose the deployment of healthcare professionals on the surveillance area who are again identified by the system with the use of RFID tags. When a patient has a healthcare professional near, then the VSN does not produce any frames for that patient as long as the patient is within the attention range of that healthcare personnel.

The healthcare professional is able to take care for a uniformly randomly located patient when the distance between them is below a threshold value which is called

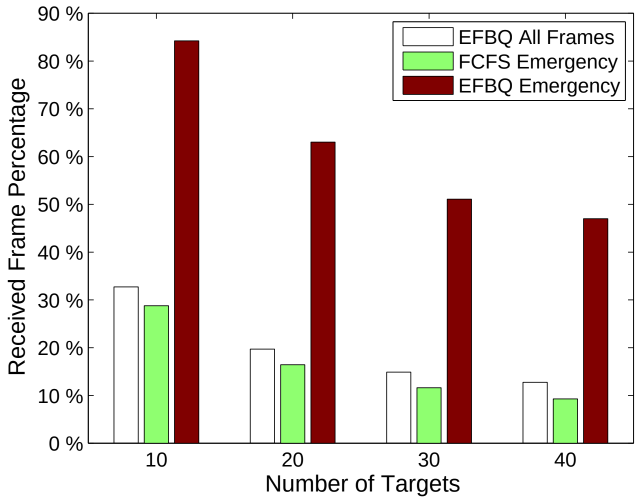


Figure 4.6. The percentages of the received frames at the source one mbps with eight fps camera frame rate

the *attention distance*. Given N healthcare professionals randomly distributed over a rectangular field, the probability of a patient is within the attention range of at least one healthcare professional can be formulated as the distance d between two random points, which are the position of the patient and the position of the healthcare professional. We assume that the length and the width of the field are D_1 and D_2 respectively with $D_1 \leq D_2$ as shown in Figure 4.7. The cumulative distribution and the probability density functions of the random variable d are provided in Equation 4.1 and Equation 4.2 respectively [106], where $\zeta = D_1/D_2 \leq 1$ is the shape parameter and $\xi = d/D_1$.

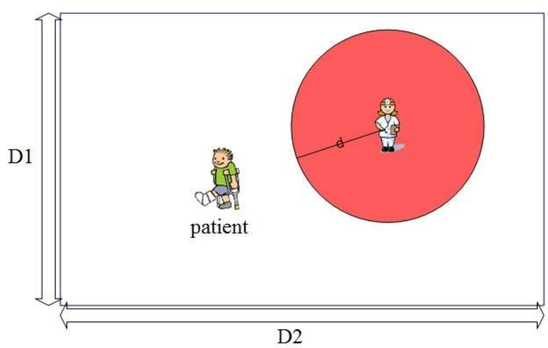


Figure 4.7. The effect of the proximity of healthcare professionals scenario

$$F(d)=\begin{cases} 0, & \xi<0 \\ \zeta\xi^2[\frac{\zeta\xi^2}{2}-\frac{4}{3}\xi(1+\zeta)+\pi], & 0\le\xi<1 \\ \frac{2}{3}\zeta\sqrt{\xi^2-1}(2\xi^2+1)-\frac{1}{6}\zeta(8\xi^3+6\zeta\xi^3-\zeta) & \\ +2\zeta\xi^3\sin^{-1}(1/\xi), & 1\le\xi<\zeta^{-1} \\ \frac{2}{3}\zeta\sqrt{\xi^2-1}(2\xi^2+1)-\frac{1}{2}\zeta^2(\xi^4+2\xi^2-\frac{1}{3}) & \\ +\frac{2}{3}\sqrt{\xi^2-\zeta^{-2}}(2\zeta^2\xi^3+1)+\frac{1}{6}\zeta^{-2}-\xi^2 & \\ +2\zeta\xi^2\sin^{-1}1/\xi-2\zeta\xi^2\cos^{-1}1/\zeta\xi, & \zeta^{-1}\le\xi<\sqrt{1+\zeta^{-2}} \\ 1, & \sqrt{1+\zeta^{-2}}\le\xi \end{cases} \tag{4.1}$$

$$f(d)=\frac{1}{D_1}\begin{cases} 2\zeta^2\xi^3+2\zeta\xi\pi-4\zeta\xi^2(1+\zeta), & 0\le\xi<1 \\ 4\zeta\xi\sqrt{\xi^2-1}-2\zeta\xi(2\xi+\zeta) & \\ +4\zeta\xi\sin^{-1}(1/\xi), & 1\le\xi<\zeta^{-1} \\ 4\zeta\xi\sqrt{\xi^2-1}+4\zeta^2\xi\sqrt{\xi^2-\zeta^{-2}} & \\ -2\xi(\zeta^2\xi^2+1+\zeta^2) & \\ +4\zeta\xi\sin^{-1}(1/\xi)-4\zeta\xi\cos^{-1}(\frac{1}{\zeta\xi}), & \zeta^{-1}\le\xi<\sqrt{1+\zeta^{-2}} \\ 0, & otherwise \end{cases} \tag{4.2}$$

With a binary detection approach $p(x)$,the attention probability of a healthcare professional, can be formulated as in Equation 4.3, where d_t is the attention distance and $x \geq 0$ is the distance between the healthcare professional and the patient.

$$p(x)=\begin{cases} 1, & x\le d_t \\ 0, & x>d_t \end{cases} \tag{4.3}$$

Therefore, the probability of a healthcare professional having a patient in his attention circle becomes

$$P(A) = \int_0^{\infty} p(x)f(x)dx = \int_0^{d_t} f(x)dx = F(d_t) \tag{4.4}$$

Since there are N healthcare professionals, the probability of a patient being monitored by k out of N healthcare professionals is a binomial distribution.

$$p(N,k) = \binom{N}{k} F(d_t)^k [1 - F(d_t)]^{N-k} \tag{4.5}$$

Equation 4.5 can be approximated by the normal distribution with $\mu = NF(d_t)$ and $\sigma^2 = NF(d_t)[1 - F(d_t)]$. Therefore, the probability that a patient will be in at least one healthcare professional's attention circle becomes

$$P(A) = 1 - p(N,0) = 1 - [1 - F(d_t)]^N \tag{4.6}$$

The attention probability for different number of healthcare professionals and for different attention distances are depicted in Figure 4.8. With an attention distance of five meters, even 20 healthcare professionals give 0.1 probability of having at least one patient in the attention area. For obtaining higher attention probabilities with 10 healthcare professionals, the attention distance must be at least 20 meters. When we increase the number of the healthcare professionals with a five meters of attention distance, the probability of attention does not improve significantly.

In Figure 4.9, we showed the effect of the number of healthcare professionals

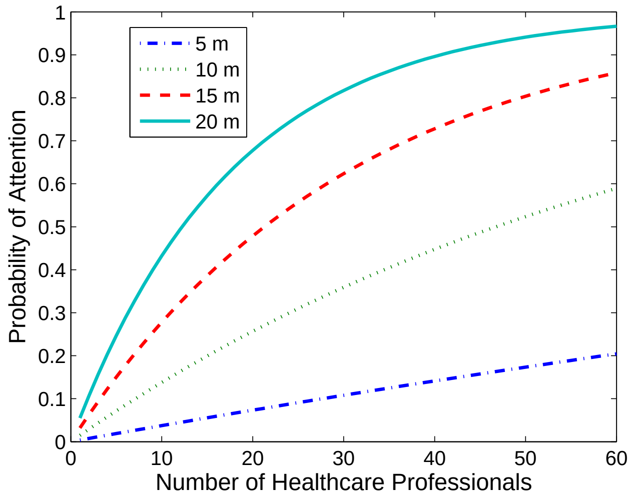


Figure 4.8. The effect of the attention distance on attention probability with $D_1 = 100$ and $D_2 = 200$

on attention probability for different attention distances. Ten healthcare professionals with a 15 meter attention distance provide nearly 0.28 probability of attention, meaning that if we deploy 10 healthcare professionals in the surveillance area, each of who is able to monitor any patient in 15 meters range, each patient will be monitored by at least one of them with a probability of 0.28. This fact is supposed to reduce the number of created frames for that patient by 28 per cent.

We simulated the effect of the attention distance of the healthcare professionals with 40 patients, 10 healthcare professionals and for different camera frame rates. The results that are tabulated in Table 4.5 are consistent with the analytical results. In the first column, the created frames per second without any healthcare professionals is given for different frame rates. In the following columns the created frames per second for 5, 10 and 15 meters of attention ranges of 10 healthcare professionals are provided for different camera frame rates. With all frame rates from one to eight frames per second, the created frames per second is reduced by approximately 28 per cent with the 15 meters attention distance. Likewise, with 10 meters attention range the reduction is approximately 12 per cent in the simulation results, whereas in the analytical solution the value is 13 per cent.

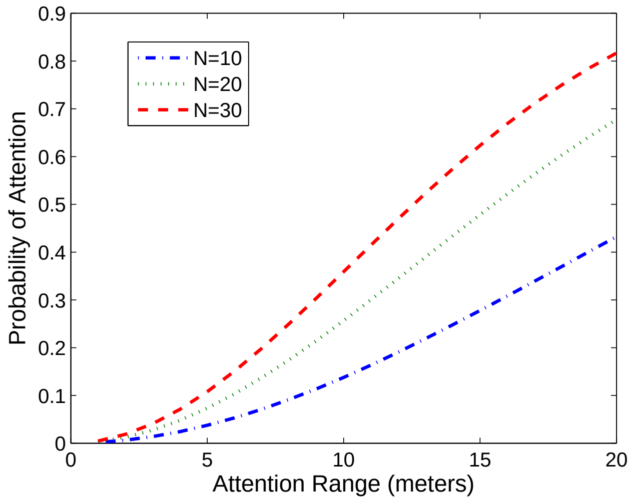


Figure 4.9. The effect of the number of healthcare professionals on attention probability with $D_1 = 100$ and $D_2 = 200$

Table 4.5. Created frames per second with different camera frame rates and different attention distance ranges

		0 m	**5 m**	**10 m**	**15 m**
Camera Frame Rate	1 fps	16.59	16.42	14.64	11.83
	2 fps	33.17	32.84	29.28	23.66
	4 fps	66.73	67.95	58.56	47.32
	8 fps	138.13	135.89	121.26	97.64

The results suggest that there are two factors affecting the attention probability of a patient given a constant number of healthcare professionals. One is the shape parameter $\zeta = D_1/D_2$ which is 0.5 in our case and the other one is $\xi = d/D_1$, the attention distance to the length of the surveillance area's shorter side ratio. This means that for different geographical areas that are having equal area sizes, we may obtain different results due to different ζ and ξ values.

5. CONCLUSION

Given the importance of addressing ways to provide smart healthcare for the elderly, chronically ill and children, exploring technological solutions to enhance health and social care provision in a way which complements existing services is becoming essential. In this thesis, we 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 surveyed systems for acquiring and interpreting context information for the ubiquitous deployment of in-house sensors. 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. A combination of different sensing modalities like video sensing, RFID, biosensors together with smart appliances and remote monitoring ability will lead context-aware, pervasive healthcare applications to become within the reach of ordinary users.

We built WeCare system in a $55m^2$ laboratory. WeCare is a wireless sensor network based application for remote healthcare monitoring of the elderly and the children especially. The multimodal sensing environment of WeCare provides a combination of different sensing modalities like video, RFID and ambient sensing. The wireless sensors provide environmental context information like the ambient light, ambient sound, temperature, and humidity. The active RFID technology is used for location tracking and also as an input for activating the video sensors i.e., if the person is in the living room then the video sensor in that room is activated for monitoring the person. In our seamless scenario, all sensors data are used to provide the context information which is then forwarded to other nomadic and mobile actors such as caregivers, parents, and healthcare professionals over the Internet and GSM. The system's flexible alarm definition and setting mechanism enhances the personalized care function.

For evaluating the performance of VSNs for an outdoor healthcare monitoring scenario, we performed a set of simulations. During wireless communication, environmental noise and packet collisions lead to packet errors frequently. Because of this, the increased traffic volume in VSNs pose significant challenges for successful arrival of the video frames at the sink. Therefore high bandwidths are needed. On the other hand, VSNs for healthcare monitoring are intended to track and monitor only the targeted patients or residents within the surveillance area. Therefore, the traffic caused by other people, animals or objects moving in the same area should be suppressed. We propose the use of small inexpensive RFID tags for this purpose so that VSNs only produce frames only for the intended targets. Moreover, when VSNs are improved with these additional sensing mechanisms, not only video frames but also physiological information will be of much importance. Furthermore, with the help of extra sensors, the emergency situations such as high blood pressure or high body temperature can be sensed and reported together with the video frames as in the case of indoor monitoring. These frames also contain life-critical information, therefore, we propose an emergency based queueing mechanism for the emergency frames in multi-hop VSN. With this feature, the video frames that contain emergency situation identifier are given priority over those that are not emergent. The video frames containing healthcare information help identifying the situation better and taking the required actions quickly. The results showed that the EFBQ mechanism significantly improved the delivery ratio of the emergency frames even under heavy traffic load.

We also investigated the effect of the proximity of the healthcare professionals to the patients. VSNs for outdoor healthcare monitoring is used in conjunction with the supervision of healthcare professionals for further improving the performance of the healthcare monitoring system. The main motivation behind this scheme is to provide the optimal use of the scarce resources like healthcare professionals and network bandwidth. Firstly, we investigated the proximity effect analytically. After that, we conducted simulations and showed that the results were compatible with the analytical solution. The shape of the surveillance area and the attention distance to the length of the surveillance area's shorter side ratio is the two important parameters for the healthcare professional enabled scenario.

For future directions, we plan to extend the capabilities of WeCare system by integrating smart home appliances to control the environment. Also, for assuring unobtrusiveness, we seek for image processing solutions for identifying the sudden falls and other physiological conditions and activity identification. For the VSNs, we will investigate different routing protocols for enabling the successful arrival of the video frames with lower latencies. Moreover, the redundant video frames generated by different sensor nodes for the same patient can be reduced by local organization of the sensor nodes among themselves. In this way, only the sensor nodes that have the closest vision produce the frames for a specific patient.

REFERENCES

1. Spencer, B. F., M. E. Ruiz-Sandoval, and N. Kurata, "Smart Sensing Technology: Opportunities and Challenges", *Structural Control and Health Monitoring*, Vol. 11, pp. 349–368, October 2004.

2. Cook, D. J., J. C. Augusto, and V. R. Jakkula, "Ambient Intelligence: Technologies, Applications, and Opportunities", *Pervasive and Mobile Computing*, Vol. 5, pp. 277–298, August 2009.

3. Kinsella, K. and D. R. Phillips, "Global Aging: The Challenge of Success", *Population Bulletin*, Vol. 60, 2005.

4. Stankovic, J. A., Q. Cao, T. Doan, L. Fang, Z. He, R. Kiran, S. Lin, S. Son, R. Stoleru, and A. Wood, "Wireless Sensor Networks for In-Home Healthcare: Potential and Challenges", *High Confidence Medical Device Software and Systems (HCMDSS) Workshop*, 2005.

5. Schmidt, A. and K. V. Laerhoven, "How to Build Smart Appliances?", *IEEE Personal Communications*, pp. 6–11, 2001.

6. Kwok, R., "Final Report : Use of 1) Sensors and 2) Radio Frequency ID (RFID) for the National Children's Study", Technical Report EPA 600/R–05/018, RTI International, 2004.

7. Choudhury, T., S. Consolvo, B. Harrison, J. Hightower, A. Lamarca, L. Legrand, A. Rahimi, A. Rea, G. Borriello, B. Hemingway, K. Koscher, J. A. Landay, J. Lester, D. Wyatt, and D. Haehnel, "An embedded Activity Recognition system", *IEEE Pervasive Computing*, pp. 32–41, 2008.

8. Stanford, V., "Using Pervasive Computing to Deliver Elder Care", *IEEE Pervasive Computing*, 2002.

9. Mcfadden, T. and J. Indulska, "Context-aware environments for independent living", *3rd National Conference of Emerging Researchers in Ageing*, pp. 1–6, 2004.

10. Virone, G., A. Wood, L. Selavo, Q. Cao, L. Fang, T. Doan, Z. He, R. Stoleru, S. Lin, and J. A. Stankovic, "An Assisted Living Oriented Information System Based on a Residential Wireless Sensor Network", *Transdisciplinary Conference on Distributed Diagnosis and Home Healthcare*, pp. 95–100, 2006.

11. Ng, H. S., M. L. Sim, C. M. Tan, and C. C. Wong, "Wireless technologies for telemedicine", *BT Technology Journal*, Vol. 24, No. 2, pp. 130–137, 2006.

12. SkyeTek, "SkyeTek M1-mini", 2009, `http://www.skyetek.com/ProductsServices/EmbeddedRFIDReaders/SkyeModuleM1mini/tabid/338/Default.aspxc`.

13. Crossbow, "MICA2DOT Wireless Microsensor Mote", 2009, `http://www.xbow.com/Products/`.

14. Harrison, M. and S. Hodges, "Demystifying RFID: principles and practicalities", Technical Report CAM-AUTOID-WHO24, AUTO-ID LABS, 2003.

15. Want, R., "An introduction to RFID technology", *IEEE Pervasive Computingp*, Vol. 5, No. 1, pp. 25–33, Jan.-March 2006.

16. Pardo, D., A. Vaz, S. Gil, J. Gomez, A. Ubarretxena, D. Puente, R. Morales-Ramos, A. Garcia-Alonso, and R. Berenguer, "Design Criteria for Full Passive Long Range UHF RFID Sensor for Human Body Temperature Monitoring", *IEEE International Conference on RFID*, pp. 141–148, March 2007.

17. Sample, A., D. Yeager, P. Powledge, and J. Smith, "Design of a Passively-Powered, Programmable Sensing Platform for UHF RFID Systems", *RFID, 2007. IEEE International Conference on*, pp. 149–156, 2007.

18. Omeni, O., O. Eljamaly, and A. Burdett, "Energy Efficient Medium Access Protocol for Wireless Medical Body Area Sensor Networks", *4th IEEE/EMBS Inter-*

national Summer School and Symposium on Medical Devices and Biosensors, pp. 29–32, August 2007.

19. Internationale, C., D. Bhatia, L. Estevez, and S. Rao, “Energy Efficient Contextual Sensing for Elderly Care”, *29th Annual International Conference of the IEEE EMBS*, pp. 4052–4055, 2007.

20. Fariborzi, H. and M. Moghavvemi, “Architecture of a Wireless Sensor Network for Vital Signs Transmission in Hospital Setting”, *2007 International Conference on Convergence Information Technology (ICCIT 2007)*, pp. 745–749, November 2007.

21. Kumar, P., “Communication in personal healthcare : Issues using 802.15.4 for personal healthcare”, *3rd International Conference Communication Systems Software and Middleware and Workshops*, 2008.

22. Lee, S. W., Y. J. Kim, G. S. Lee, B. O. Cho, and N. H. Lee, “A Remote Behavioral Monitoring System for Elders Living Alone”, *International Conference on Control, Automation and Systems*, pp. 2725–2730, 2007.

23. Ren, H. and Q. H. M. Max, “Bioeffects Control in Wireless Biomedical Sensor Networks”, *3rd Annual IEEE Communications Society on Sensor and Ad Hoc Communications and Networks*, Vol. 3, pp. 896–904, September 2006.

24. Seo, J., J. Heo, S. Lim, J. Ahn, and W. Kim, “A Study on the Implementation of a Portable u-Healthcare System using SNMP and AODV”, *29th Annual International Conference of the IEEE EMBS*, pp. 1519–1522, 2007.

25. Lahtela, A., M. Hassinen, and V. Jylha, “RFID and NFC in Healthcare: Safety of Hospitals Medication Care”, *Pervasive Computing Technologies for Healthcare*, 2008.

26. Lee, Y. and W. Chung, “Wireless sensor network based wearable smart shirt for

ubiquitous health and activity monitoring", *Sensors and Actuators B: Chemical*, May 2009.

27. Lee, H. J., S. H. Lee, K. S. Ha, H. C. Jang, W. Y. Chung, J. Y. Kim, Y.-S. Chang, and D. H. Yoo, "Ubiquitous healthcare service using Zigbee and mobile phone for elderly patients", *International Journal of Medical Informatics*, Vol. 78, pp. 193–8, March 2009.

28. Morris, D., S. Coyle, Y. Wu, K. T. Lau, G. Wallace, and D. Diamond, "Bio-sensing textile based patch with integrated optical detection system for sweat monitoring", *Sensors and Actuators B: Chemical*, Vol. 139, pp. 231–236, May 2009.

29. Nyan, M. N., F. E. H. Tay, and E. Murugasu, "A wearable system for pre-impact fall detection", *Journal of Biomechanics*, Vol. 41, pp. 3475–81, December 2008.

30. Varshney, U., "A framework for supporting emergency messages in wireless patient monitoring", *Decision Support Systems*, Vol. 45, pp. 981–996, November 2008.

31. Lai, C. C., R. G. Lee, C. C. Hsiao, H. S. Liu, and C. C. Chen, "A H-QoS-demand personalized home physiological monitoring system over a wireless multi-hop relay network for mobile home healthcare applications", *Journal of Network and Computer Applications*, May 2009.

32. Benhaddou, D., M. Balakrishnan, and X. Yuan, "Remote Healthcare Monitoring System Architecture using Sensor Networks", *Region 5 Conference*, pp. 1–6, 2008.

33. Bao, S., Y. Zhang, and L. Shen, "Physiological Signal Based Entity Authentication for Body Area Sensor Networks and Mobile Healthcare Systems", *27th Annual International Conference of the IEEE EMBS*, pp. 2455–2458, 2005.

34. Dağtas, S., G. Pekhteryev, Z. Sahinoğlu, H. Çam, and N. Challa, "Real-time and

secure wireless health monitoring", *International Journal of Telemedicine and Applications*, Vol. 2008, pp. 1–10, January 2008.

35. García-Sáez, G., M. E. Hernando, I. Martínez-Sarriegui, M. Rigla, V. Torralba, E. Brugués, A. De Leiva, and E. J. Gómez, "Architecture of a wireless Personal Assistant for telemedical diabetes care", *International Journal of Medical Informatics*, Vol. 78, pp. 391–403, June 2009.

36. Tu, Y., W. Zhou, and S. Piramuthu, "Identifying RFID-embedded objects in pervasive healthcare applications", *Decision Support Systems*, Vol. 46, pp. 586–593, January 2009.

37. Lamprinos, I. E., A. Prentza, E. Sakka, and D. Koutsouris, "Energy-efficient MAC Protocol for Patient Personal Area Networks", *27th Annual International Conference of the IEEE EMBS*, pp. 3799–3802, 2005.

38. Chen, S., H. Lee, Y. Chu, C. Chen, and C. Lin, "A Variable Control System for Wireless Body Sensor Network", *IEEE International Symposium on Circuits and Systems*, pp. 2034–2037, 2008.

39. Terzis, A., A. Watt, J. Jeng, B. Chen, K. Lorincz, and M. Welsh, "Wireless Medical Sensor Networks in Emergency Response: Implementation and Pilot Results", *Second International Conference on Pervasive Computing Technologies for Healthcare*, 2008.

40. Osmani, V., S. Balasubramaniam, and D. Botvich, "Human activity recognition in pervasive health-care: Supporting efficient remote collaboration", *Journal of Network and Computer Applications*, Vol. 31, pp. 628–655, 2008.

41. Chung, W., C. Yau, and K. Shin, "A Cell Phone Based Health Monitoring System with Self Analysis Processor using Wireless Sensor Network Technology", *29th Annual International Conference of the IEEE EMBS*, 2007.

42. Pawar, P., B. Vanbeijnum, M. Vansinderen, a. Aggarwal, P. Maret, and F. Declercq, "Performance evaluation of the context-aware handover mechanism for the nomadic mobile services in remote patient monitoring", *Computer Communications*, Vol. 31, pp. 3831–3842, October 2008.

43. Leister, W. and H. Abie, "Threat Assessment of Wireless Patient Monitoring Systems", *3d International Conference On Information & Communication Technologies: From Theory To Applications*, 2008.

44. Hu, F., M. Jiang, L. Celentano, and Y. Xiao, "Robust medical ad hoc sensor networks (MASN) with wavelet-based ECG data mining", *Ad Hoc Networks*, Vol. 6, pp. 986–1012, September 2008.

45. Kuran, M. S. and T. Tugcu, "A survey on emerging broadband wireless access technologies", *Computer Networks*, Vol. 51, No. 11, pp. 3013–3046, 2007.

46. Karshmer, A., M. Becker, and R. Lamm, "Living Assistance Systems - An Ambient Intelligence Approach -", *The International Conference on Software Engineering (ICSE)*, 2006.

47. Lee, H. and K. Park, "Issues in Data Fusion for Healthcare Monitoring", *1st international conference on Pervasive Technologies Related to Assistive Environments*, 2008.

48. Casas, R., R. Blasco Marín, A. Robinet, A. R. Delgado, A. R. Yarza, J. Mcginn, R. Picking, and V. Grout, "User Modelling in Ambient Intelligence for Elderly and Disabled People", *ICCHP '08: Proceedings of the 11th International Conference on Computers Helping People with Special Needs*, pp. 114–122, Springer-Verlag, Berlin, Heidelberg, 2008.

49. Jasemian, Y., "Elderly comfort and compliance to modern telemedicine system at home", *Second International Conference on Pervasive Computing Technologies for Healthcare*, 2008.

50. Triantafyllidis, A., V. Koutkias, I. Chouvarda, and N. Maglaveras, "An Open and Reconfigurable Wireless Sensor Network for Pervasive Health Monitoring", *Second International Conference on Pervasive Computing Technologies for Healthcare*, 2008.

51. Lopez, T. S. and D. Kim, "Wireless Sensor Networks and RFID integration for Context Aware Services", Technical Report, Auto-ID Labs White Paper, 2008.

52. Moya-fernández, J. M., "PERSEIA: a Biomedical Wireless Sensor Network to Support Healthcare Delivery for the Elderly and Chronically Ill", *28th Annual International Conference of the IEEE EMBS*, 2006.

53. Waluyo, A. B., S. Ying, I. Pek, and J. K. Wu, "Middleware for Wireless Medical Body Area Network", *IEEE Biomedical Circuits and Systems Conference*, pp. 183–186, 2007.

54. Lu, H. and J. Chen, "Design of middleware for tele-homecare systems", *Wireless Communications and Mobile Computing*, 2009.

55. Atallah, L., B. Lo, G. Yang, and F. Siegemund, "Wirelessly accessible sensor populations (WASP) for elderly care monitoring", *Second International Conference on Pervasive Computing Technologies for Healthcare*, pp. 2–7, 2008.

56. Gao, T., D. Greenspan, M. Welsh, R. R. Juang, and A. Alm, "Vital Signs Monitoring and Patient Tracking Over a Wireless Network", *27th Annual International Conference of the IEEE EMBS*, 2005.

57. Dey, A. K. and G. D. Abowd, "Towards a Better Understanding of Context and Context-Awareness", *1st International Symposium on Handheld and Ubiquitous Computing*, 1999.

58. Ng, J., B. Lo, O. Wells, M. Sloman, N. Peters, A. Darzi, C. Toumazou, and G. Yang, "Ubiquitous Monitoring Environment for Wearable and Implantable

Sensors (UbiMon)", *6th International Conference on Ubiquitous Computing*, 2004.

59. Yang, G., B. Lo, L. Wang, M. Rans, S. Thiemjarus, J. Ng, P. Garner, S. Brown, B. Majeed, and I. Neid, "From Sensor Networks to Behaviour Profiling: A Home-care Perspective of Intelligent Building", *IEE Seminar for Intelligent Buildings*, 2004.

60. Paganelli, F. and D. Giuli, "An Ontology-Based Context Model for Home Health Monitoring and Alerting in Chronic Patient Care Networks", *AINAW '07: Proceedings of the 21st International Conference on Advanced Information Networking and Applications Workshops*, pp. 838–845, IEEE Computer Society, Washington, DC, USA, 2007.

61. Paganelli, F., E. Spinicci, and D. Giuli, "ERMHAN: a context-aware service platform to support continuous care networks for home-based assistance", *International Journal of Telemedicine Applications*, Vol. 2008, pp. 1–13, 2008.

62. Kim, J., H. Kwon, D. Kim, H. Kwak, and S.-J. Lee, "Building a Service-Oriented Ontology for Wireless Sensor Networks", *Seventh IEEE/ACIS International Conference on Computer and Information Science (ICIS 2008)*, pp. 649–654, 2008.

63. Wang, H., X. Zhou, and Z. Wang, "Supporting the Living of the Elderly with Semantic Collaborative HealthCare", *Second International Conference on Pervasive Computing Technologies for Healthcare*, 2008.

64. Philipose, M., J. R., B. Jiang, A. Mamishev, S. Roy, and K. Sundara-rajan, "Battery-Free Wireless Identification and Sensing", *Pervasive Computing*, 2005.

65. Philipose, M., S. Consolvo, I. Smith, D. Fox, H. Kautz, and D. Patterson, "Fast, Detailed Inference of Diverse Daily Human Activities", *UbiComp 2003: Fifth International Conference on Ubiquitous Computing*, 2003.

66. Consolvo, S., P. Roessler, and B. E. Shelton, "The CareNet Display: Lessons Learned from an In Home Evaluation of an Ambient Display", *6th International Conference on Ubiquitous Computing*, pp. 1–17, 2004.

67. Sung, M., C. Marci, and A. Pentland, "Wearable Feedback Systems for Rehabilitation", *Journal of Neuroengineering and Rehabilitation*, Vol. 2, p. 17, 2005.

68. DeVaul, R., M. Sung, J. Gips, and A. Pentland, "MIThril 2003: applications and architecture", *Seventh IEEE International Symposium on Wearable Computers*, pp. 4 – 11, 2003.

69. Patel, S., K. Lorincz, R. Hughes, N. Huggins, J. H. Growdon, and M. Welsh, "Analysis of Feature Space for Monitoring Persons with Parkinson's Disease With Application to a Wireless Wearable Sensor System", *29th IEEE EMBS Annual International Conference*, 2007.

70. Yin, J., Q. Yang, S. Member, and J. J. Pan, "Sensor-Based Abnormal Human-Activity Detection", *IEEE Transactions on Knowledge and Data Engineering*, Vol. 20, pp. 1082–1090, 2008.

71. Stikic, M., T. Huynh, K. Van Laerhoven, and B. Schiele, "ADL Recognition Based on the Combination of RFID and Accelerometer Sensing", *Second International Conference on Pervasive Computing Technologies for Healthcare*, pp. 258–263, 2008.

72. Logan, B., J. Healey, M. Philipose, E. Munguia, and S. Intille, "A Long-Term Evaluation of Sensing Modalities for Activity Recognition", *Lecture Notes in Computer Science*, Vol. 4717, pp. 483–500, 2007.

73. Bowser, S. and J. Woodworth, "Wireless Multimedia Technologies for Assisted Living", *Second LACCEI International Latin American and Caribbean Conference for Engineering and Technology*, June 2004.

74. Chang, Y., C. Chen, L. Chou, and T. Wang, "A Novel Indoor Wayfinding System Based on Passive RFID for Individuals with Cognitive Impairments", *Second International Conference on Pervasive Computing Technologies for Healthcare*, pp. 108–111, 2008.

75. Marco, A., R. Casas, J. Falco, H. Gracia, J. Artigas, and a. Roy, "Location-based services for elderly and disabled people", *Computer Communications*, Vol. 31, pp. 1055–1066, 2008.

76. Yan, H., Y. Xu, M. Gidlund, and R. Nohr, "An Experimental Study on Home-Wireless Passive Positioning", *2008 Second International Conference on Sensor Technologies and Applications (SENSORCOMM 2008)*, pp. 223–228, August 2008.

77. Moh, M., Z. Walker, T. Hamada, and C.-f. Su, "A Prototype on RFID and Sensor Networks for Elder Healthcare: Progress Report", *ACM SIGCOMM workshop on Experimental approaches to wireless network design and analysis*, pp. 70–75, 2005.

78. López-nores, M., J. J. Pazos-arias, J. García-duque, and Y. Blanco-fernández, "Monitoring Medicine Intake in the Networked Home: The iCabiNET Solution", *Second International Conference on Pervasive Computing Technologies for Healthcare*, 2008.

79. Helal, S., C. Giraldo, Y. Kaddoura, C. Lee, H. E. L. Zabadani, and W. Mann, "Smart Phone Based Cognitive Assistant", *2nd International Workshop on Ubiquitous Computing for Pervasive Healthcare Applications*, 2003.

80. Konstantas, D. and R. Herzog, "Continuous monitoring of vital constants for mobile users: the MobiHealth approach", *25th Annual lnternational Conference of the IEEE EMBS*, pp. 3728–3731, 2003.

81. Wood, A. D., J. A. Stankovic, G. Virone, L. Selavo, Z. He, Q. Cao, T. Doan, Y. Wu, L. Fang, and R. Stoleru, "Context-Aware Wireless Sensor Networks for

Assisted Living and Residential Monitoring", *IEEE Network*, pp. 26–33, 2008.

82. Baker, C., K. Armijo, S. Belka, M. Benhabib, V. Bhargava, N. Burkhart, A. Der Minassians, G. Dervisoglu, L. Gutnik, M. Haick, C. Ho, M. Koplow, J. Mangold, S. Robinson, M. Rosa, M. Schwartz, C. Sims, H. Stoffregen, A. Waterbury, E. Leland, T. Pering, and P. Wright, "Wireless Sensor Networks for Home Health Care", *21st International Conference on Advanced Information Networking and Applications Workshops*, Vol. 2, pp. 832–837, May 2007.

83. Yang, C. M. and T. L. Yang, "A Vital Wearing System with Wireless Capability", *Second International Conference on Pervasive Computing Technologies for Healthcare*, 2008.

84. Kailanto, H., E. Hyvärinen, J. Hyttinen, and R. G. Institute, "Mobile ECG Measurement and Analysis System Using Mobile Phone as the Base Station", *Second International Conference on Pervasive Computing Technologies for Healthcare*, 2008.

85. Lee, D., Y. Lee, W. Chung, and R. Myllyla, "Vital Sign Monitoring System with Life Emergency Event Detection using Wireless Sensor Network", *IEEE Sensors*, pp. 518–521, 2006.

86. Shnayder, V., B. Chen, K. Lorincz, T. R. F. Fulford-Jones, and M. Welsh, "Sensor Networks for Medical Care", *3rd International Conference on Embedded Networked Sensor Systems*, 2005.

87. Lorincz, K. and M. Welsh, "Motetrack: A robust, decentralized approach to rf-based location tracking", *Lecture Notes in Computer Science*, Vol. 3479, pp. 63–82, 2005.

88. Montgomery, K., C. Mundt, G. Thonier, A. Tellier, U. Udoh, V. Barker, R. Ricks, L. Giovangrandi, P. Davies, Y. Cagle, J. Swain, J. Hines, and G. Kovacs, "Lifeguard- A Personal Physiological Monitor For Extreme Environments", *26th*

Annual International Conference of the IEEE Engineering in Medicine and Biology Society, 2004.

89. Li, Z., A. Engineering, and H. Kong, "A Physical Activities Healthcare System Based on Wireless Sensing Technology", *13th IEEE International Conference on Embedded and Real-Time Computing Systems and Applications*, 2007.

90. Zhou, B., C. Hu, H. Wang, and R. Guo, "A Wireless Sensor Network for Pervasive Medical Supervision", *International Conference on Integration Technology*, pp. 740–744, 2007.

91. Jones, V. M., H. Mei, T. Broens, I. Widya, and J. Peuscher, "Context Aware Body Area Networks for Telemedicine", *8th Pacific Rim Conference on Multimedia*, 2007.

92. Martí, R., S. Robles, A. Martín-Campillo, and J. Cucurull, "Providing early resource allocation during emergencies: The mobile triage tag", *Journal of Network and Computer Applications*, May 2009.

93. Lin, C., R. Lee, and C. Hsiao, "A pervasive health monitoring service system based on ubiquitous network technology", *International Journal of Medical Informatics*, Vol. 77, pp. 461–469, July 2008.

94. Nummela, A., "A Concept for Personal Wellness Management Based on Activity Monitoring", *Second International Conference on Pervasive Computing Technologies for Healthcare*, 2008.

95. Hori, T. and Y. Nishida, "Ultrasonic sensors for the elderly and caregivers in a nursing home", *Seventh International Conference on Enterprise Information Systems*, pp. 110–115, 2005.

96. Purwar, A., D. U. Jeong, and W. Y. Chung, "Activity Monitoring from Real-Time Triaxial Accelerometer data using Sensor Network", *International Conference on*

Control, Automation and Systems, pp. 2402–2406, 2007.

97. Leijdekkers, P., V. Gay, and E. Lawrence, “Smart Homecare System for Health Tele-monitoring”, *First International Conference on the Digital Society*, 2007.

98. Hansen, T. R., J. M. Eklund, J. Sprinkle, R. Bajcsy, and S. Sastry, “Using smart sensors and a camera phone to detect and verify the fall of elderly persons”, *European Medicine, Biology and Engineering Conference*, 2005.

99. Tabar, A. M. and H. Aghajan, “Smart Home Care Network using Sensor Fusion and Distributed Vision-based Reasoning”, *4th ACM international workshop on Video surveillance and sensor networks*, pp. 145–154, 2006.

100. Iso-ketola, P., T. Karinsalo, and J. Vanhala, “HipGuard: A Wearable Measurement System for Patients Recovering from a Hip Operation”, *Second International Conference on Pervasive Computing Technologies for Healthcare*, 2008.

101. Takeda, R., S. Tadano, M. Todoh, M. Morikawa, M. Nakayasu, and S. Yoshinari, “Gait analysis using gravitational acceleration measured by wearable sensors.”, *Journal of Biomechanics*, Vol. 42, pp. 223–33, February 2009.

102. Fan, K., Z. Zheng, and P. Sinha, “Steady and fair rate allocation for rechargeable sensors in perpetual sensor networks”, *SenSys*, pp. 239–252, 2008.

103. Ye, W., J. Heidemann, and D. Estrin, “Medium access control with coordinated adaptive sleeping for wireless sensor networks”, *IEEE/ACM Transactions on Networking*, Vol. 12, pp. 493–506, 2004.

104. Karp, B., “GPSR: Greedy perimeter stateless routing for wireless networks”, *In ACM MOBICOM*, 2000.

105. NORDIC-Semiconductors, “nRF2401A Transceiver”, July 2009, `http://www.nordicsemi.com/`.

106. Miller, L. E., "Distribution of Link Distances in a Wireless Network", *Journal of Research of the National Institute of Standards and Technology*, Vol. 106, pp. 401–412, 2001.