Part I: *System*

Tele-Healthcare
Monitoring Networks

CHAPTER

1

Wearable Healthcare-Monitoring Systems Using E-textiles and Wireless Sensor Networks

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Introduction

The demand for smart healthcare services which allow monitoring patient status in a noninvasive manner, anywhere and anytime, is increasing as a means to counter costly welfare systems and increasing elderly population [1], [2]. As a result, much research has been carried out in this area during the past few years [3], [4].

Standing out among the new emerging technologies that can be applied to this field are e-textiles and Wireless Sensor Networks (WSNs).

Advances in nanotechnology and smart materials have led to so-called e-textiles which enable measuring biometric parameters in a noninvasive manner. Using e-textiles, wearable healthcare monitoring systems can be developed avoiding the use of cables wired around the patient, as the current practice is.

Table 1. Table of Acronyms.

AGPS	Assisted-Global Position System
BP	Beacon Point
DAPB	Data Acquisition and Processing Board
DP	Distribution Point
DSR	Dynamic Source Routing
ECG	Electrocardiogram
E-OTD	Enhanced Observed Time Difference
ETB	Ethernet Transmission Board
GSM	Global System for Mobile Communication
GUI	Graphical User Interface
IT	Information Technology
LBS	Location Based Services
LQI	Link Quality Indicator
MAC	Media Access Control
MTU	Maximum Transfer Unit
Nchannels	Number of channels available for sending location beacons
Pbeacons	Period BPs send beacons with
PDA	Personal Digital Assistant
PCB	Printed-Circuit Board
Ptx_loc	Period of time WTBs send location information with
QoS	Quality of Service
RFID	Radio Frequency IDentification
RSS	Received Signal Strength
SMS	Short Message Service
TDoA	Time Difference of Arrival
Tlisten	Time WTBs spend listening to each channel available for location
ToA	Time of Arrival
UWB	Ultra Wide Band
WDAD	Wearable Data Acquisition Device
WLAN	Wireless Local Area Network
WSN	Wireless Sensor Network
WTB	Wireless Transmission Board

Advances in microelectronics and communications have led to WSNs, which can be applied to develop smart healthcare systems in different ways. On the one hand, networks of smart sensors can be deployed on the body of the patient making up so-called Body Area Network (BAN) [5], [6]. On the other hand, WSNs can form a low-cost and low-consumption communications infrastructure to support wide coverage and mobility (i.e. pervasiveness), which allow natural movement of patients and potential development of value- added services.

This chapter will focus on the latter application of WSNs and their combination with e-textile technologies to develop next-generation healthcare systems especially targeting hospital environments. In particular, it will present a real-world healthcare IT platform to monitor several physiological parameters, such as ECG, heart rate, angle of inclination, activity index and body temperature, and to track the location of a group of patients within hospital facilities [7]. The chapter provides a practical approach from a system engineering perspective, from the requirement definition up to the client-side validation of the platform at the Cardiology Unit of La Paz Hospital (in Madrid, Spain), by way of the design and development details.

Table 2 summarizes some of the most relevant works in this specific area [8]–[14] and compares them to the one that represents the center of this chapter.

System Requirements

System requirement engineering represents a key issue to successfully design and develop complex systems, in general, and next-generation smart healthcare systems, in particular. The basic procedure entails translating user requirements (provided by the users or stakeholders) into system requirements, the designer engineers being responsible for this magic [15]. This section provides a practical view of such procedure by presenting the most important system requirements of this healthcare platform, which were worked out by the development partners from the user requirements set by the personnel of La Paz Hospital. Most of these requirements are common to every Wearable Healthcare-Monitoring System, especially to those targeting hospital environments.

Some of the most important requirements that worked as guidelines for the subsequent design, development, and validation phases of the project are listed below.

- The system must allow monitoring multiple physiological parameters (namely, ECG, heart rate, angle of inclination, activity index, and body temperature) and tracking the location of a group of patients within hospital facilities.
- The device used to acquire the physiological information must be wearable, noninvasive, comfortable, and washable.
- The autonomy of the devices must be at least the duration of a work shift (i.e., approximately 8 hours).

Table 2. Related Works.

	Target Application	Wireless Technology	Health Status Monitoring	e-Textile based	Data Acquisition Modes	Location	System Capacity Analysis	Validation in Real Environments
LOBIN [7]	Hospital environments	WSN (802.15.4)	Yes	Yes	Continuously On-demand After any alarm	Yes Indoor location	Yes	Yes
AMON [8]	Telemedicine	GSM	Yes	No	Periodically	No		Yes
Life-Guard [9]	Adventurers	Bluetooth	Yes	No	Locally recorded Continuously	No		Yes
MagIC [10]	Telemedicine Clinical Environments		Yes	Yes	Continuously	No	No	Yes
WEALTHY [11]	Telemedicine	GPRS	Yes	Yes	Quasi-realtime	No		Yes
CodeBlue [12]	Hospital environments	WSN (802.15.4)	Yes	No	Continuously Indoor location	Yes	No	No
Smart Vest [13]	High-risk workers	Proprietary from Xtream in the ISM band (2.4 GHz)	Yes	Yes	Continuously	Yes Geolocation (GPS)		Yes
Lee et al [14]	Sport	WSN (802.15.4)	Yes	Yes	Continuously	No	No	Yes

- The location algorithm must be accurate enough to correctly determine the hospital room where a given patient is actually located.
- The system must locate patients within the space qualified for their stay (e.g., hospital unit, hospital floor).
- The system must support al least 5 patients providing such a degree of QoS that ensures that the percentage of lost packets is not higher than 2% of those sent.
- The system must allow managing patients' profiles (e.g., add, modify, delete).
- The system must store all the physiological data associated with a patient for some period of time.
- The system must provide reports with all the medical parameters of a given patient during a period of time.
- The system must allow configuring alarms by setting different triggers associated with each patient.
- The system must be versatile enough to allow both monitoring, in a noninvasive manner, critical physiological parameters of patients who suffer high-risk diseases and have very low mobility (e.g., ECG of patients suffering diseases of the heart and blood vessels and who, are usually, confined to bed) and obtaining other ordinary parameters from patients whose health is not so weak and who have medium mobility (e.g., temperature monitoring of patients in a hospital).
- The system must support the transmission of certain parameters explicitly under request (i.e., on-demand) or after any alarming incident occurs.

Due to the nature of the data managed by this kind of system, security and privacy also represent two key requirements to be covered. However, this chapter will not address them in detail, since they were out-of-the-scope of the LOBIN project [7].

System Architecture

This section presents the architecture and main features of Wearable Healthcare-Monitoring Systems using the work in [7] as example.

Figure 1 shows the overall architecture designed to meet the specific requirements presented in the previous section. Such architecture is composed of the following subsystems:

- The *Healthcare-Monitoring Subsystem* consists of the set of smart shirts to be worn by the patients. Every smart shirt is

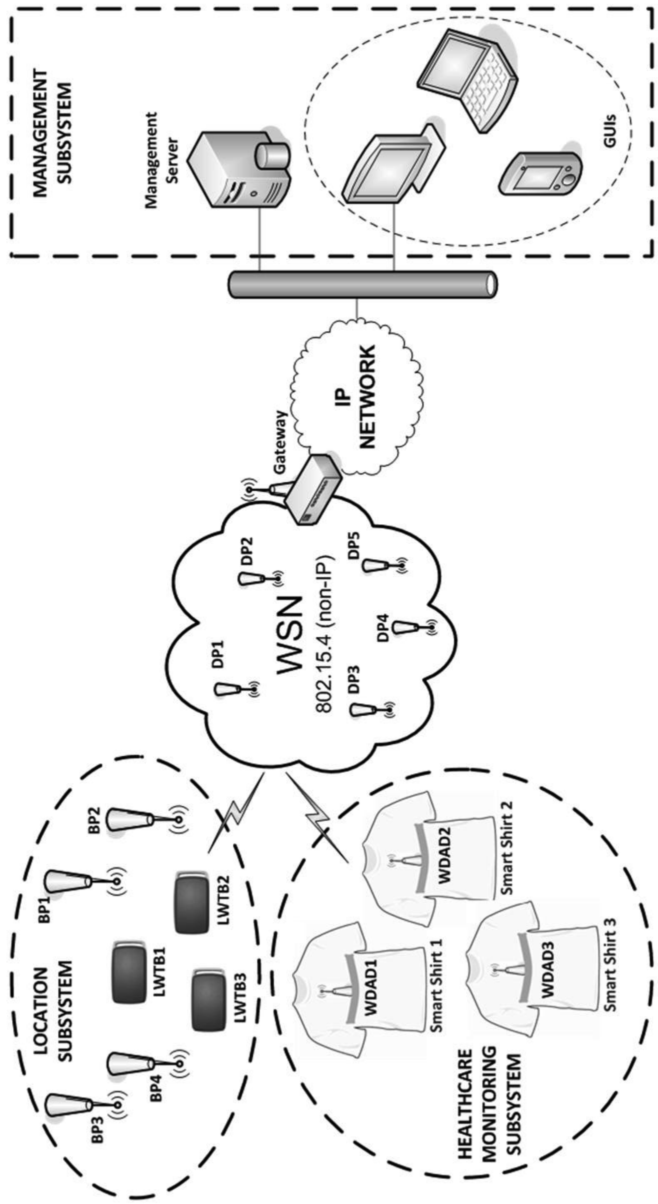

Figure 1. System Architecture.

provided with a device (so-called Wearable Data Acquisition Device—WDAD), which collects and processes the physiological parameters and transmits them wirelessly.

- The *Location Subsystem* consists of a set of Beacon Points (BPs), which are deployed in well-known positions, and a set of end devices (so-called Location Wireless Transmission Boards—LWTBs), which are carried by targeted users (e.g., patients or any other personnel from the hospital). The BPs, as their name suggests, send beacons periodically with well-known transmission power. The WTBs collect signal strength information received from different BPs and send it wirelessly.
- The *Wireless Sensor Network Subsystem* is placed in between the *Location* and *Healthcare-Monitoring Subsystems* and the *Management Subsystem*. It is responsible for carrying data from the former to the latter and commands from the latter to the former. It consists of a set of devices (so-called Distribution Points—DPs) that transmit *ad hoc* data up to a Gateway, which forwards them to the *Management Subsystem*. Thus, the Gateway interfaces with the WSN (non-IP-based) and with the wired communications infrastructure (IP-based) connected to the *Management Subsystem*.
- The *Management Subsystem* represents the Information Technology (IT) infrastructure that handles the information associated with every single patient. It consists of a Management Server, which processes and stores all the data associated with the patients, and a Graphical User Interface (GUI), which allows the hospital staff to monitor the status of the patients. This subsystem can be integrated into commercial hospital management systems.

Next, each subsystem is explained in detail.

Healthcare Monitoring Subsystem

Over the last few years, monitoring devices based on multifunctional instrumented garments have been playing an innovative role in the development of more human-oriented monitoring systems. Such biomonitoring systems have recently evolved considerably due to the appearance of smart fabrics. The technology of smart fabrics allows adding functionalities to textiles. The original idea comes from the study of biological systems, where organic and inorganic materials are combined in an effective way. Smart fabrics of special interest to this work are the conductive fabrics (e-textiles), which combine conductive materials (either metallic or non-metallic) with organic textiles, such as nylon or lycra.

E-textiles allow a comfortable and user-friendly way to monitor a patient's health status over extended periods of time. As a result, their areas of applications are many, such as bio-monitoring, telemedicine, home healthcare, rehabilitation, or sport medicine [16], [17].

The *Healthcare Monitoring Subsystem* presented in this chapter relies on e-textile technology. It consists of a set of smart shirts. Every smart shirt is equipped with physiological sensors and a WDAD, which processes the data coming from the sensors and transmits them wirelessly. The WDAD is further divided into two different PCBs: the Data Acquisition and Processing Board (DAPB) and the WTB. Figure 2 sketches how the *Healthcare Monitoring Subsystem* works.

The physiological sensors are in charge of measuring raw data that will be further processed in order to obtain the required biomedical parameters. The available sensors are: the e-textile electrodes, the accelerometer, and the thermometer. The e-textile electrodes are used to measure the bioelectric potential of the human body and are integrated into the smart shirt, as shown in Figure 3. The signals provided by the 3-axis accelerometer are used to detect patient movements and determine whether the patient is laying down or moving about in order to aid appropriate diagnosis. The thermometer measures the body temperature and it must be in direct contact with the skin of the patient. Both the 3-axis accelerometer and the thermometer are integrated into the WDAD, as it is also shown in Figure 3.

The DAPB collects all the data from the sensors, processes them, merges them all together in a message (i.e., the healthcare-monitoring subsystem frame) and sends them via a serial port to the WTB. Figure 4 sketches the internal operation of the DAPB.

The WTB builds a new packet by adding information related to the WSN to the message coming from the DAPB and transmits it wirelessly. Both the DAPB and the WTB share the same battery so they can be integrated into a common PCB for commercialization. Figure 5 shows the developed hardware.

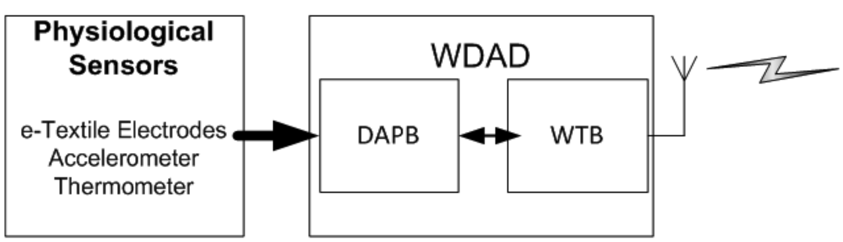

Figure 2. Healthcare Monitoring Subsystem Block Diagram.

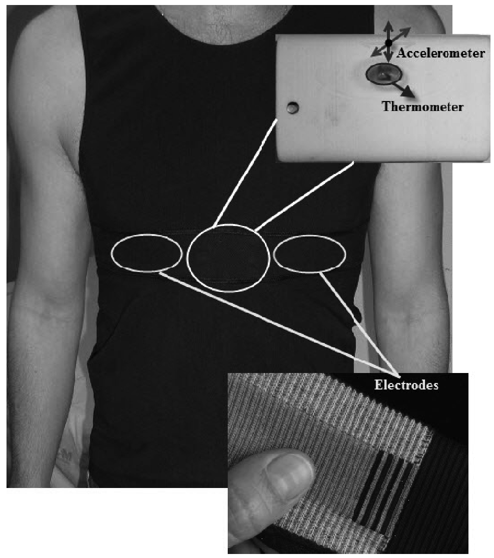

Figure 3. Smart Shirt, Physiological Parameters, and WDAD.

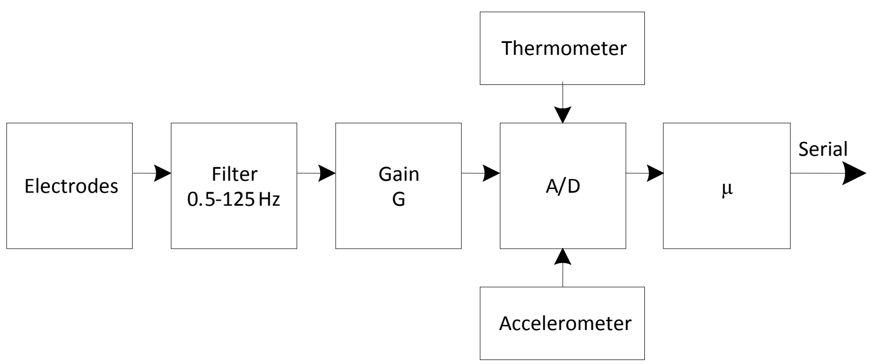

Figure 4. DAPB Block Diagram.

As has already been mentioned, a healthcare-monitoring frame to pack all the sensitive information in just one message, is defined. All the physiological parameters are sampled every 4 ms. However, this message is only transmitted after collecting 65 ECG samples. This value is determined by the size of the frame resulting from the healthcare-monitoring frame together with the additional routing information, needing to be as close as possible to the 802.15.4 MTU (102 bytes). As a result of this decision, efficiency is maximized and transmission rates decreased, which in turn reduces collisions in the WSN. Thus, from the *Management Subsystem* point of view, the rest

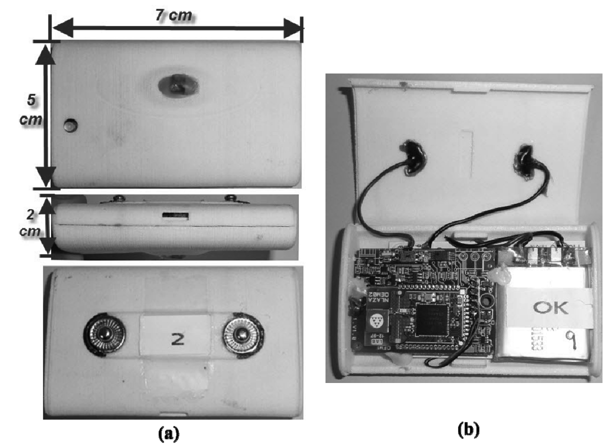

Figure 5. (a) WDAD (b) Healthcare Monitoring WTB and battery.

of the parameters apart from the ECG are sampled every 260 ms. Table 3 summarizes the most important features of the parameters transmitted in this message.

Location Subsystem

Currently, user location represents a hot topic for the industry due to the fact that Location Based Services (LBSs) are winning momentum and popularity, since they can be used to provide added value to a wide variety of applications.

There are many different methods in the state-of-the-art to compute the location of a user [18], [19], such as Cell Global Identity (used in WLAN/GSM), Angle of Arrival (AoA), Received Signal Strength (RSS), Time of Arrival (ToA), Time Difference of Arrival (TDoA), or Enhanced Observed Time Difference (E-OTD). The suitability of each method depends on whether the localization is outdoor or indoor and on the communications technology used.

As for indoor localization, much research has been carried out recently and many different solutions using different technologies, such as Assisted-GPS (AGPS) [20], 802.11 [21], Bluetooth [22]–[24], RFID [25], [26], Ultra Wide Band (UWB) [27], or 802.15.4/Zigbee [12], have been explored. The use of each technology implies some benefits and drawbacks that make it more or less suitable depending on the targeted scenario.

During the development phase of the *Location Subsystem* presented in this chapter, the performance of three different indoor localization algorithms was compared in real environments:

Table 3. Summary of Healthcare Monitoring Subsystem Parameters.

Parameter	Features
ECG	Frequency: 0.5-125 Hz Amplitude: ~ 0-50 mV Gain: G1 byte/sample 65 samples/tx packet
Heart rate	Computed from ECG 1 byte/sample 1 sample/tx packet
Angle of inclination	Computed from 3-axis accelerometer 1 byte/sample 1 sample/tx packet
Activity index	Computed by averaging angle of inclination 1 byte/sample 1 sample/tx packet
Body temperature	Range: -20ºC to 120ºC Accuracy: 0.1ºC Valid range: 32ºC to 45ºC 1 byte/sample 1 sample/tx packet
Level of battery	100-0% Coverage: 8-9 hours 1 byte/sample 1 sample/tx packet
Alert	To carry alert code if necessary 1 byte/sample 1 sample/tx packet

- Algorithm based on triangulation. It derives the distance from the received signal strength in two ways: (a) by means of the Friis formula; (b) by using regressions based on empirical measurements taken within the target indoor scenario. In both cases, the obtained results do not fit reality and the users' actual locations are not determined accurately. Therefore, this location algorithm was ruled out.
- Algorithm that does not use the Link Quality Indicator (LQI) to determine the user's actual position. The LQI measurement is a characterization of the strength and/or quality of a received packet [28]-[30]. However, this algorithm locates the target at the geometrical center of all the BPs it receives beacons from. Hence, this algorithm always locates the user within the area comprised by the appropriate BPs, but it offers very poor precision, which in turn depends strongly on the distance between BPs, and so on the transmitted power. Therefore, this location algorithm was also ruled out.

- Algorithm based on Weighted Centroid Localization (WCL) and the LQI. The WCL algorithm [31] consists of computing a point comprised within the area covered by the BPs the target received beacons from, so that this point will be closer to those BPs from where higher LQIs are received. In order to do so, different weights (directly proportional to the received LQI) are assigned to every received beacon. This algorithm is the one used in the *Location Subsystem* presented here since it was proved to yield the best results.

The *Location Subsystem* consists of two different devices: BPs and LWTBs. Figure 6 sketches how the *Location Subsystem* works.

The BPs are deployed in well-known positions and are plugged into the electricity supply network. They send beacons periodically in one of the four channels scheduled for location purposes (namely, IEEE 802.15.4 channels 11, 12, 13, and 14) using a fixed and well-known transmission power.

The LWTBs are carried by the users and are in sleep mode most of the time. Periodically (eventually, every 9 s, as explained in section *Location Subsystem Tests*), they wake up and listen to every single channel available for location purposes in order to record the LQI received from the different BPs. Note that the time that the LWTBs are listening to a given channel has to be at least twice the time between beacons from a given BP in order to avoid beacon losses. Once these data is collected, the LWTBs merge them into a single message (i.e., the location subsystem frame), add some necessary network layer information and send it to the *Management Subsystem*

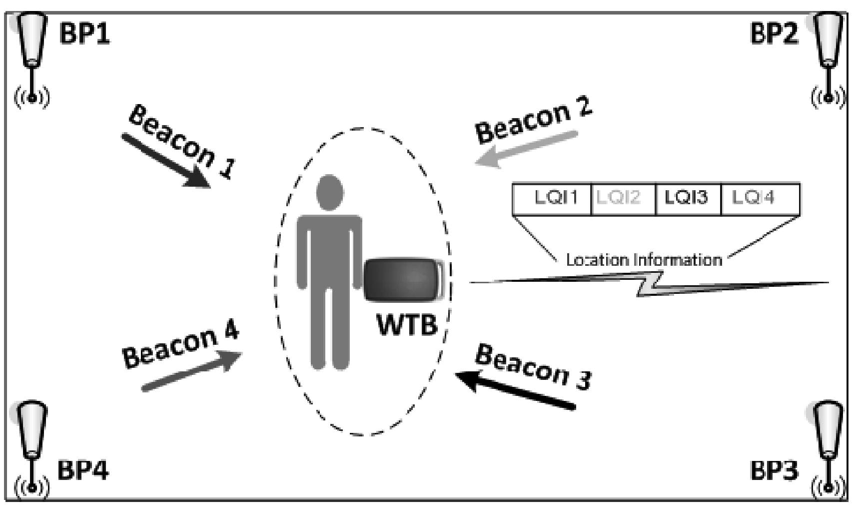

Figure 6. Location Subsystem Operation.

through the *WSN Subsystem*. Figure 7 shows the developed BP and LWTB.

The location subsystem frame consists of a set of pairs [BP identifier, LQI]. This set is preceded by a field that identifies the number of transmitted pairs up to a maximum of 80, which is more than enough taking into account the areas to be covered by the system and the transmission range of the BPs. The location of the patients is computed at the *Management Subsystem*—using such pairs and the WCL algorithm—and then drawn onto a 2-D plan—given that the BPs' locations are known. It is worthwhile to remark on the fact that the location algorithm needs at least four pairs [BP identifier, LQI] in order to work properly.

Wireless Sensor Network Subsystem

WSNs are small networks that require low bandwidth, low power consumption and low deployment and maintenance costs. Recently, they have become increasingly important in the telecommunication industry because of their wide range of applications.

In order to promote and encourage the incorporation of such networks in a competitive market, the IEEE has defined the 802.15 family of standards that deal with the Physical and Media Access Control (MAC) layers. Within this family of standards, it is especially relevant to the work presented in this chapter the Low-Rate Wireless Personal Area Networks IEEE 802.15.4 [28]–[30], that was designed for applications with low transmission rate, very low power consumption, and relaxed QoS requirements.

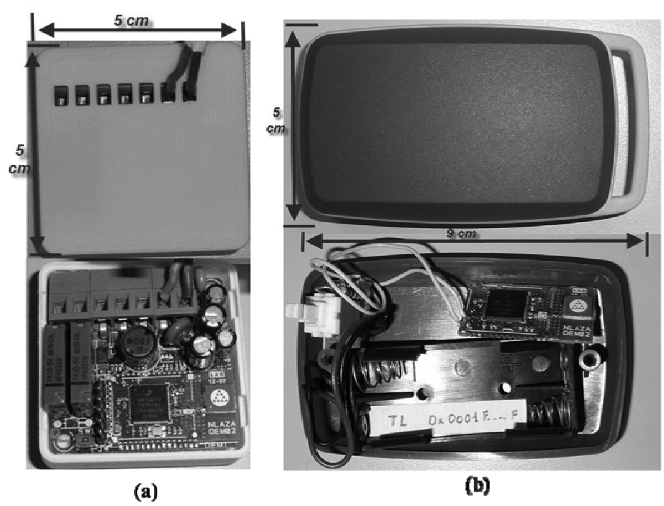

Figure 7. (a) BP (b) LWTB.

Although the Zigbee Alliance addresses the upper layers (namely, Network and Application) and proposes several routing algorithms to be used at the network layer, over the last few years much research has been carried out in order to design and develop routing algorithms that fit the many restrictions of such networks in an effective way [32]–[35]. These restrictions have to do mainly with the limitations of the available hardware (e.g., battery, memory, computing capacity) and with some other issues associated with wireless communications, such as scarce bandwidth or collisions.

The scenario considered here adds some additional complexity to the problem, since it presents an asymmetric traffic pattern. Most of the information is sent from the patients to the *Management Subsystem* (uplink), since patients are sources of data; whereas only a few commands travel in the other direction, i.e., from the *Management Subsystem* to the patients (downlink). As a result, a routing algorithm that fits such special features has been designed and developed on top of IEEE 802.15.4 [36].

The *WSN Subsystem* represents the wireless communications infrastructure of the system presented in this chapter. It consists of a network of DPs that transmit data—coming from the WDADs and the LWTBs—*ad-hoc* up to a Gateway, which forwards them to the *Management Subsystem*. The overall *WSN Subsystem* architecture is shown in Figure 1.

DPs are deployed all over the targeted areas and they are plugged to the electricity supply network. From the hardware point of view, they are exactly the same as the BPs, the only difference being the software that runs on them.

The Gateway incorporates a wireless interface and an Ethernet (IEEE 802.3) interface. They are in charge of forwarding all the data coming from the WSN to the *Management Subsystem*. They are plugged into the electricity supply network. They implement full routing functionality, exactly as DPs do. Moreover, WDADs and LWTBs can send data straight through them. A Gateway consists of two different PCBs: the WTB and the Ethernet Transmission Board (ETB). The communications between both PCBs is performed via a serial port at 115600 bauds. This value was set for the Gateway to be able to forward, without problems, the aggregate traffic coming from the WSN. Figure 8(a) sketches how the Gateway works and Figure 8(b) shows the Gateway.

The routing algorithm used in the *WSN Subsystem* is a source routing algorithm based on Dynamic Source Routing (DSR) [37]. When a DP is turned on, it queries its neighbour DPs to discover how to reach the destination (i.e., the Gateway). Thereafter, it receives responses, which contain different paths to do so. The first received

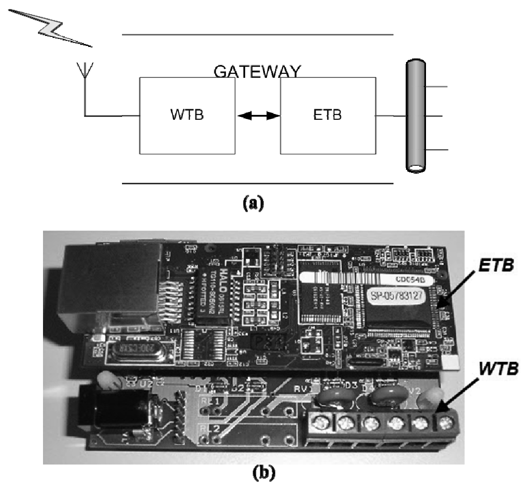

Figure 8. (a) Gateway Block Diagram (b) Gateway, composes of WTB and ETB.

response is stored as the default route. The following responses (up to 2) are stored as back-up routes. Before storing such routes, it is checked that they do not contain the same DP several times in order to avoid loops. In addition, DPs exchange, periodically, status information with their neighbours. Nevertheless, since the targeted scenario is very stable, this period is set to a high value (namely, minutes) in order to reduce the overhead introduced into the WSN. If a DP realizes that the default path is down either while transmitting a packet or after exchanging routing information, it can use one of the other default paths to solve the problem immediately. If there is no back-up path available in the DP at any given moment, the path discovery procedure is triggered again [36].

In order to save memory in the DPs, they are not aware of the end nodes (namely, Healthcare Monitoring WTBs or LWTBs) that are associated with them, i.e., they do not store such information in memory. However, end nodes do store the DP they are associated with. If, either because the end node roams from one DP to another or because the DP it is associated with goes down, the end node realizes its DP is no longer available and it looks for other DPs to send the data through. Furthermore, in order to save battery life, end nodes are not involved in routing [36].

In order to avoid possible interferences with the *Location Subsystem*, as well as with other widespread communication technologies such as IEEE 802.11 [38], the 802.15.4 channel 25 is used for communication within the WSN, since it is the furthest one from the channels used to broadcast location beacons.

Management Subsytem

The Management Subsystem is based on a client-server architecture (shown in Figure 9), the Management Server being the server and the GUIs being the clients.

The Management Server was developed using C as programming language. It runs on Fedora, which is an operating system built on top of the Linux kernel. It uses an Oracle database (DDBB) to store the information associated with the patients. The DDBB provides an independent interface with the GUI, thus allowing the development of tailored user applications to cover additional functionalities.

The GUI was developed in Java, which provides it with great flexibility and allows it to run on any platform without problems, a computer, a PDA or a mobile. The developed GUI meets the system requirements, since it allows managing patients' profiles, monitoring all the medical parameters of any patient in real-time, locating any patient within the hospital facilities, verifying if any alarm has been activated, as well as sending an SMS including this information if required.

The Management System also provides tools for managing maps and BPs' locations, so that this application can be implemented in any hospital without modifying the software of the location module.

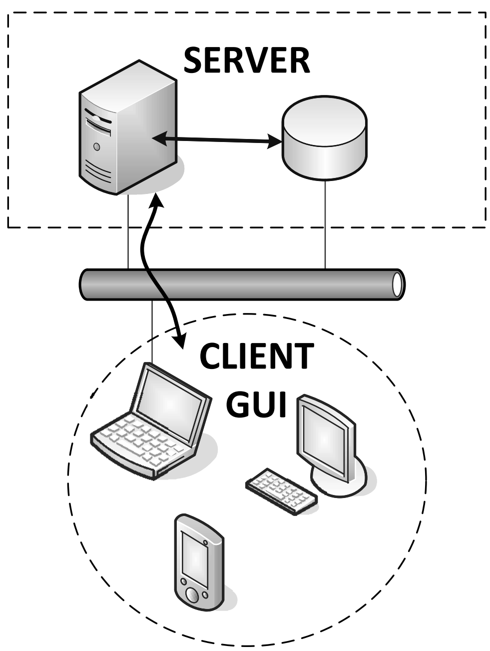

Figure 9. Management Subsystem Client-Server Architecture.

Experimental Results and Lessons Learned

This section aims at illustrating the different phases involved in the validation of *Wearable Healthcare-Monitoring Systems*, based on the experiences and lessons learned in LOBIN project [7]. Thus, the next subsections describe how each subsystem was debugged and validated separately, as well as the validation of the overall system in a real scenario (namely, a pilot scheme deployed in the Cardiology Unit of La Paz Hospital, Madrid, Spain), putting special emphasis on the main problems found and how they were overcome.

Management Subsystem tests are not described in a specific section. However, typical software development tests were applied to this subsystem in order to check its behaviour and performance during the development phase. Furthermore, usability tests were performed during the client-side validation process (i.e., tests in real scenario).

Healthcare Monitoring Subsystem Tests

The performance of the *Healthcare Monitoring Subsystem* was checked with a set of laboratory tests. Such tests were planned twofold.

The main goal of the first subset of tests was to verify that the sensors collect real data and that the WDAD processes and transmits these data correctly. In order to verify the correct processing of the bioelectric potentials, the values sent by the WDAD were compared with the original values generated in the laboratory using the generator NI USB 628 from National Instrument. In addition to simulating normal ECG signals, different arrhythmias were also tested with the aim of verifying the operation of the alarms.

To verify that the body temperature sensor works properly, its values were compared with the values of a commercial thermometer, concluding that the temperature taken by the thermometer integrated into the WDAD takes about 5 minutes to acquire an accurate value. The accelerometer tests were performed manually by tilting the device to known angles.

Figure 10 shows the interface that was developed for this first validation stage using LabVIEW. This tool was used to verify every biometrical parameter, i.e., ECG, heart rate, angle of inclination, activity index and temperature, as well as to check that the ECG representation allows perfectly identifying the waves and intervals of the heartbeat (namely, the P wave, the QRS complex, and the T wave).

The second subset of tests verifies that the subsystem works in an environment closer to the actual target. The main goal of this stage was to check qualitatively that the e-textile electrodes work properly when in direct contact with a human body.

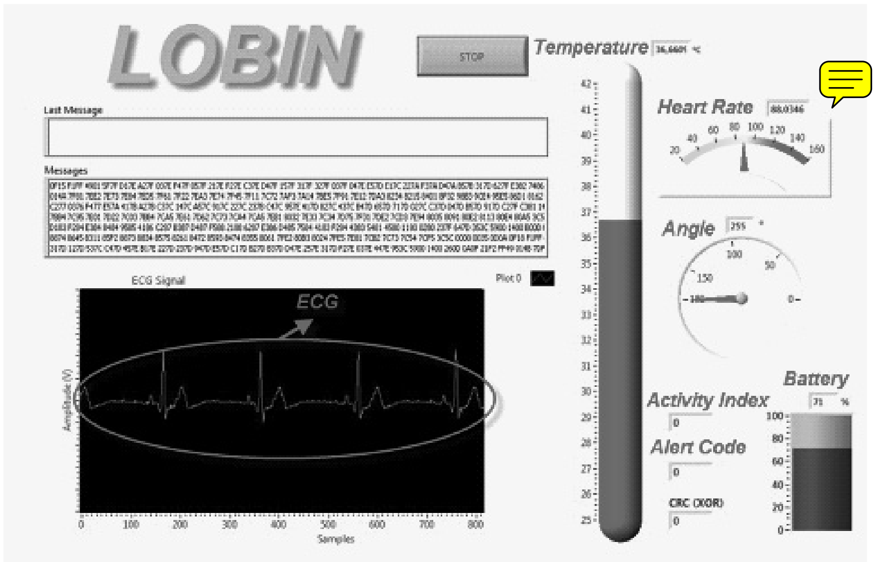

Figure 10. Healthcare Monitoring Subsystem Debugging Interface.

These tests were performed by using both a standalone e-textile belt and one that was integrated into the shirt. When the patients were not carrying out activities that required very vigorous movements, both e-textile-based devices yielded good results. However, during sudden movements, such as standing up or jumping about, both results worsened slightly. Even so, the electrodes integrated in the shirt performed better in such situations since the shirt helps to maintain sensor contact with the user's chest. If some conductive substance (e.g., water or conductive gel) was applied to the electrodes, the effects of sudden movements to the quality of the ECG signals were, in both cases, mitigated. In addition, the ECG signal quality in such situations can be further enhanced by filtering the noise taking advantage of the signals provided by the 3-axis accelerometer [14].

Location Subsystem Tests

The objective of these tests was twofold: (a) to verify that the developed location algorithm worked in real scenarios; (b) to select the most appropriate values for the parameters and to study their impact on the performance of the location algorithm. Thus, the *Location Subsystem* tests can be divided into two different subsets.

The main goal of the first subset of tests was to explore how the number of BPs and the distances between them impact the accuracy of the location algorithm. In order to achieve this goal, BPs were first deployed at the roof following rectangular grids of 100, 225, and 400 m^2 (see Figure 11), the best results being obtained for the rectangular grids of the smallest area. Thus, it was proved that the closer the BPs are, the better the location algorithm performs, since it is most unlikely that a LWTB loses a beacon from a BP or that a LWTB receives beacons from less than four BPs. However, the closer they are, the more expensive the deployment is, because more BPs are needed to cover the same area. Anyway, it was concluded as design criterion that the sub-rectangles of the BP grid network should not exceed 100 m^2.

However, it is also necessary to locate users over wider areas. Hence, additional tests were carried out in order to verify whether the system still worked correctly when deploying a rectangular grid with more BPs. Following the design criterion mentioned in the previous paragraph, the scenario shown in Figure 12 was tested, where 8 BPs were deployed to cover an area similar to the area of the target scenario (around 300 m^2).

In such a scenario, channel assignment of each BP is not random. As a deployment criterion, it is recommended to place the BPs operating on the same channel as far from each other as possible. These rules are not mandatory, since theoretically the channels in IEEE 802.15.4 are independent, but in practice its use is highly recommended to avoid possible interference, which may modify the LQI of the received beacons.

The accuracy in the location of the LWTBs for the scenario shown in Figure 12 was proved to be very similar to the accuracy obtained previously for the scenario of just 100 m^2, so it was concluded that the system scales properly.

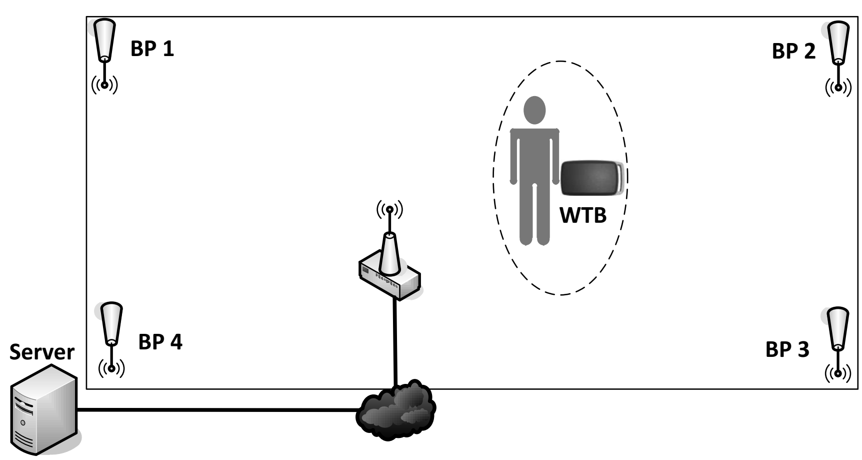

Figure 11. BP density test.

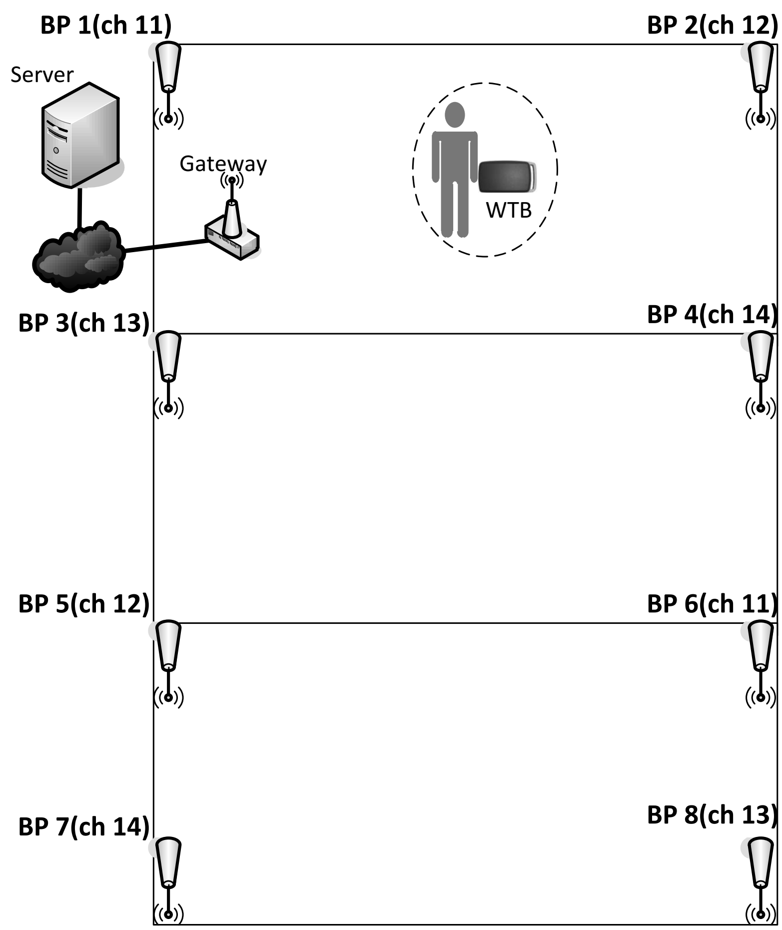

Figure 12. Scalability test.

The main goal of the second subset of test was to maximize the performance of the *Location Subsystem* for the chosen DP deployment configuration by tuning different parameters. The parameters that were considered are:

- The period of time LWTBs send information with (*Ptx_loc*)
- The period of time BPs send beacons with (*Pbeacons*)
- The time LWTBs spend listening to each location channel from the 4 available ones (*Tlisten*)

Note that the lower *Ptx_loc* is selected, the more accurate the patients' locations drawn in the map are, since the *Management*

Server receives location information more frequently; but the LWTBs spend more battery because they send information more frequently. Furthermore, it has to be taken into account that *Ptx_loc* must always be higher than the time the LWTBs need to listen to the 4 channels available for location (1) and that *Tlisten* must be at least twice *Pbeacons* (2) in order to ensure there is enough time to receive at least one beacon.

$$Ptx\_loc \geq Tlisten \cdot Nchannels \tag{1}$$

$$Tlisten \geq 2 \cdot Pbeacons \tag{2}$$

The five configurations shown in Table 4 were tested and it was checked qualitatively that the configuration set in test number 5 performed better than the others, so it was selected for deployments in real scenarios.

In this configuration, *Ptx_loc* was set to the minimum value (9 seconds) in order to reduce the latency and improve the location of patients when they were moving around. This location update time represents a trade-off between battery power consumption and location latency that meets the system requirements, since the location in strict real-time is not necessary in hospital environments due to the low/medium user mobility. In order to reduce the probability of losing a beacon, *Tlisten* was set to 4 times *Pbeacons*. Hence, if a beacon was lost, there was still enough time to receive at least two more beacons, thus improving significantly the stability of the location algorithm.

The margin of error of the location algorithm was proved to be around 2 m^2, thus meeting the system requirements. This margin of error improves the results obtained [31], despite the fact that the results presented in [31] were obtained outdoors. This is mainly because the BPs are placed much closer to one another in this case than in the experiments carried out in [31] (10m × 10m in these tests and 43 m × 43 m in [31]). However, this accuracy is similar to the one reported [12], where the location algorithm is based on Received Signal Strength Indication (RSSI) signatures.

Table 4. Location Subsystem Configurations.

Test	Ptx_loc (s)	Tlisten (s)	Pbeacons (s)
1	30	2	1
2	9	2	1
3	20	4	1
4	15	2	0.5
5	9	2	0.5

Wireless Sensor Network Subsystem Tests

These tests tried to verify that the WSN meets the system requirements. Therefore, different network topologies were explored in order to select the one that supports at least 5 users with a guarantee that the percentage of lost packets is lower than 2% of those sent.

The first test deployment was composed of a network of DPs and a Gateway. In order to cover approximately 300 m^2, 5 DPs and 1 Gateway were deployed, as shown in Figure 13.

Obtained results show that this topology does not support high data rate applications. Figure 14 shows that the percentage of lost packets increases non-linearly with the number of patients

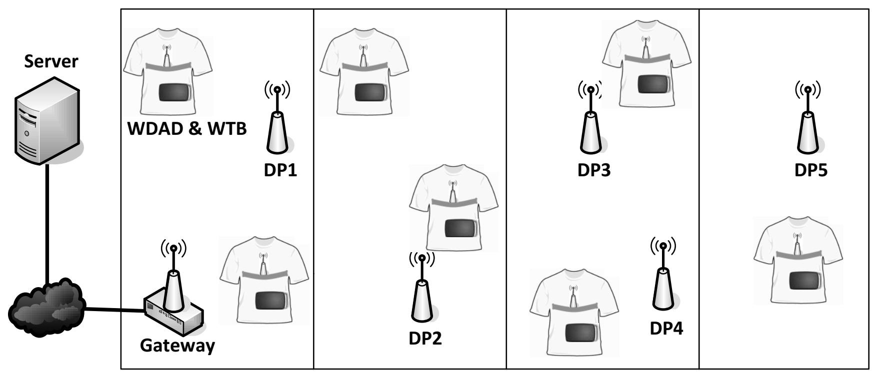

Figure 13. Network of DPs.

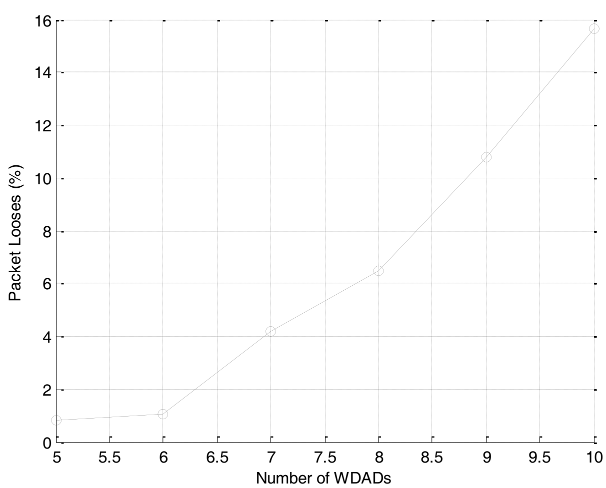

Figure 14. Results obtained when testing the network of DPs.

and exceeds the maximum loss percentage allowed greatly. This is due to the fact that the traffic handled by the network does not grow linearly with the number of patients, but is higher, since it not only increases the traffic added by the sources, but also the traffic forwarded by the DPs. Similar issues were also reported [12].

As a result, this configuration is suitable for applications that present low traffic load, but require high coverage (e.g., ordinary temperature checking on-demand or location fixing); but it does not work for high data rate applications, such as real-time ECG monitoring, since it does not support more than 6 WDADs sending messages every 260 ms (~ 3.1 Kbps/WDAD).

The same network topology (i.e., DP network) duplicating the deployed infrastructure was also tested. In this scenario, two different IEEE 802.15.4 channels were used within the WSN in order to split the traffic. Several pairs of channels (namely, 24-25 and 18–25) were tested and none of them yielded the expected improvement. Thus, it can be concluded that in such scenarios that present heavy traffic load, interference between IEEE 802.15.4 channels may occur with subsequent high data losses. Furthermore, this approach entails some drawbacks, such as the fact that WDADs and LWTBs have to be programmed to work in one channel or another or that the network infrastructure needs to be duplicated, which means an increase on the deployment cost.

Finally, the DP network was replaced by a network of Gateways, as shown in Figure 15. This topology was proved to provide the best results, presenting the lowest percentage of losses in scenarios with 8–10 matched WDAD and LWTBs. This percentage of loses was tested to be with a 95 % confidence in the interval (0.2068%, 1.6585%) for 10 tests of about 15 minutes duration involving 10 users. Therefore, the obtained data were considered to fit a Gaussian distribution and the 95% confidence interval was computed using the formula below, μ being the mean of the data, σ the standard deviation of the data, and n the length of the data (i.e., n = 100):

$$(\mu - 1.96 \cdot \frac{\sigma}{\sqrt{n}}, \mu + 1.96 \cdot \frac{\sigma}{\sqrt{n}})$$

This approach adds redundancy to the system and supports user mobility better, since patients may be within the coverage of different Gateways and so data may be forwarded to the *Management Server* several times, reducing the probability of packet loses even when a patient is moving. As a result, the reliability of the system is improved.

However, this WSN configuration also presents some drawbacks, such as the fact that wired infrastructure is required (namely,

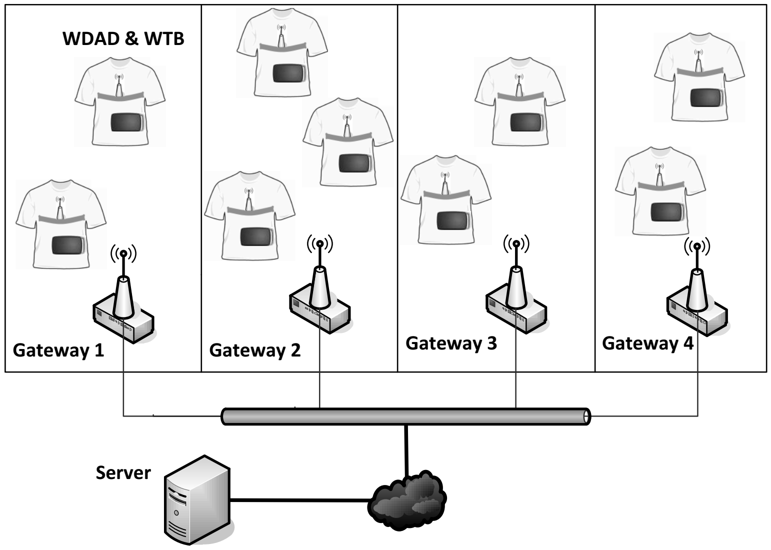

Figure 15. Network of Gateways.

Ethernet) and that the number of duplicated packets in the *Management Server* increases dramatically, although this is not a problem since bandwidth is not an issue in the wired communications segment and the *Management Server* handles packets much faster than the rate they arrive with.

Overall System Tests

After debugging and tuning each subsystem separately, the performance of the whole system was tested in a real scenario by deploying a pilot scheme in the Cardiology Unit at La Paz Hospital (Madrid, Spain). For this client-side validation, each subsystem was set up following the design criteria and conclusions from previous tests. Figure 16 illustrates the coverage area and network infrastructure that was deployed for the pilot scheme.

The tests carried out at the hospital facilities involved 5 patients (i.e., 5 WDADs and 5 LWTBs) and run for 24 hours. Such tests were considered successful, since the results obtained results met the expected ones (and so the requirements of the system):

- Percentage of packet losses was lower than the maximum acceptable value (i.e., 2%)
- Battery life was proved to be about 8-9 hours for WDADs and two days for LWTBs
- The location algorithm was tested to work properly

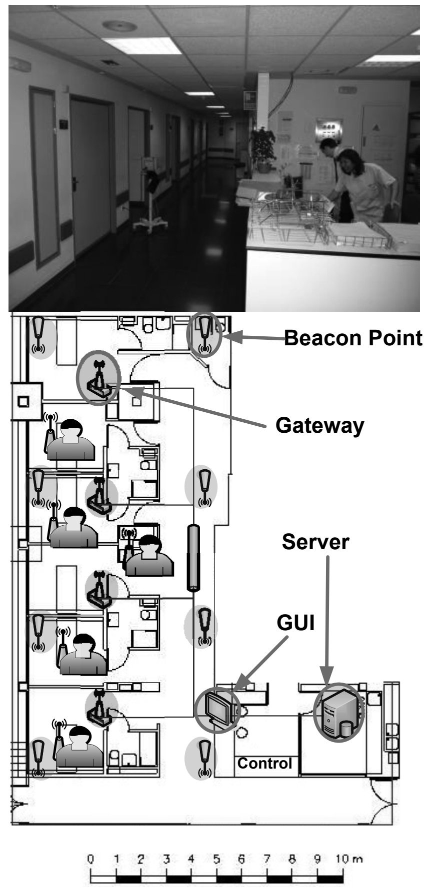

Figure 16. Pilot scheme schematics.

- Measured physiological parameters were normal and met expected values
- The quality of the real-time ECG signals was approved by hospital doctors

In addition, hospital personnel provided valuable feedback to improve the quality and usability of the system, such as:

- The tightness of the smart shirt was pointed out as an issue by hospital personnel, since patients from Cardiology Unit often present high abdominal perimeter. Nevertheless, no further complains were received.
- Hospital staff use the GUI both to monitor the patients' status in real-time easily, sitting in front of a PC, and to look at the

signals over a long period of time, taking advantage of the features provided by the tool. Some of these features, such as checking just a given period of time by selecting initial time and final time or the scroll, were incorporated into the GUI on the request of hospital personnel.

- The ECG display was modified following the feedback from the hospital personnel in order to fit the ECG representation they are used to handle (e.g., from commercial electrocardiographic devices).

Figure 17 shows the developed GUI, where the health status of five patients can be monitored at a glance and the ECG of one of them is displayed. The tool also includes a Geographic Information System (GIS) to locate the patients in the hospital facilities plan.

Conclusions and Outlook

This chapter provides a practical view, from a system engineering perspective, of *Wearable Healthcare Monitoring Systems* through the work done and lessons learned [7].

The chapter details the design, development, and validation phases of a real-world hardware and software IT platform, based on e-textile and WSN as most innovative technologies, to monitor a set of physiological parameters from a group of patients and to locate

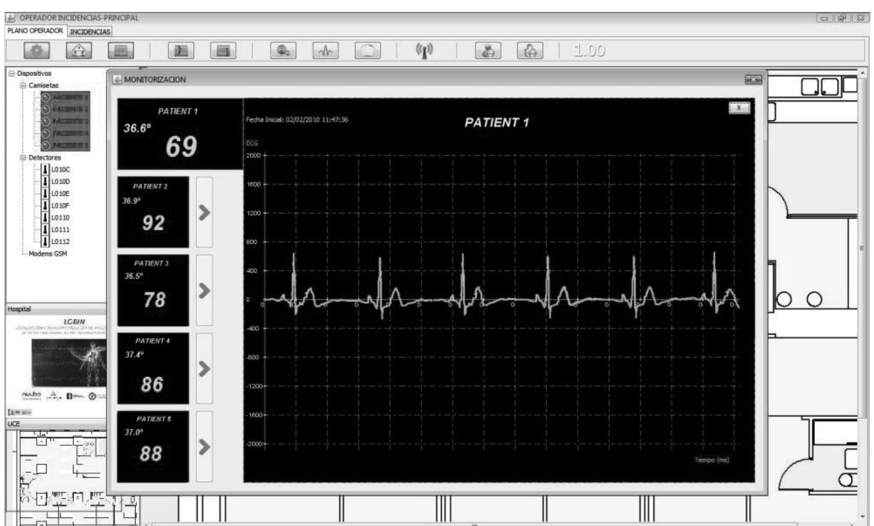

Figure 17. Developed GUI.

them (or any other personnel from the hospital if desired) within hospital facilities.

The most important issues found when developing and validating each subsystem, as well as the whole system, are presented together with the solutions applied and the results obtained.

Regarding the performance of the WSN infrastructure, this work proves that an *ad hoc* network (i.e., a network of DPs) does not perform properly under heavy traffic load scenarios, such as 5 patients transmitting the ECG in real-time. Other communications technologies which provide higher data rates, such as Bluetooth or IEEE 802.11, might be applied in such cases, but they would dramatically reduce the battery lifetime, which represents a key system requirement. Therefore, a network of Gateways is proposed in this work as a successful solution to provide the required degree of QoS in these situations, since it increases the reliability of the wireless communications infrastructure by adding redundancy and mobility support. Nevertheless, the DP network infrastructures are suitable for other applications that present low traffic load, but require high coverage, such as ordinary temperature checking on-demand or location fixing.

The presented architecture, which decouples *Healthcare Monitoring* and *Location Subsystems*, supports both scenarios. On the one hand, a network of Gateways can be deployed to monitor in a noninvasive manner critical physiological parameters of patients who suffer high-risk diseases and present very low mobility (e.g., ECG of patients who suffer from disease of heart and blood vessels); on the other hand, a network of DPs can be deployed to monitor ordinary parameters, such as body temperature, either on-demand or periodically, from a large number of patients spread over a wide area (e.g., a hospital floor).

The chapter also remarks upon future research lines and improvements to the presented system. Regarding the *Healthcare Monitoring Subsystem*, the ECG signal acquired by the e-textile electrodes can be improved, especially when sudden movements happen, by filtering the noise taking advantage of the information provided by the 3-axis accelerometer. The indoor location feature can be further exploited to develop new LBSs which make the system smarter and more sophisticated (e.g., a service where the location of hospital staff is tracked in order to alert the appropriate person who is closest about an eventual problem). Finally, the presented system can be applied to other environments introducing few changes, e.g., it can be used seamlessly for telemedicine applications just providing the patient with a smart shirt and a Gateway at home.

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