WEARABLE WIRELESS MONITORING SYSTEM BASED ON BLUETOOTH TECHNOLOGY: A TUTORIAL

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Abstract: The medical technology is making the remote monitoring systems to progress towards the called wearable systems where several sensors acquire the patient's biomedical and environmental information and transmit it to some near receiver. These acquisition devices are called wearable and environmental sensors and they have reduced dimensions, high autonomy and wireless communication ability among others features. Short range wireless communication between the sensors and the near receiver plays an important role in these new systems. In this paper the use of Bluetooth technology in these short range communications is described. Likewise, the basic features that justify its use are explained.

Introduction

Last advances in Information and Communication Technologies have made Telemedicine to be one of the fields with more interest in society and research groups. This discipline is changing the classical concept of "patient" and his role in the health system in two ways. On one hand, sophisticated methods and devices for the treatment of diseases are being developed. On the other hand, new health service models that make possible to know the patient's health state with minimal influence on his daily activities are being provided. These health services are based on remote monitoring systems which perform the acquisition, processing and transmission of the patient's biomedical parameters (ECG, blood pressure, weight …) and environmental information (temperature, position, daily habits …) to some faraway health centre, wherever the patient is. Once the information is received, a specialist or health worker can analyze it and contact the patient in case of necessity.

Nowadays medical technology aims for the development and use of "wearable" remote monitoring systems. These systems are the first step towards an environment characterized by a perfect relation between people and all the technological devices used for the diagnosis, treatment and control of diseases. This ideal environment is known as Ambient Intelligent [1][2].

The main goal of wearable systems is to carry out the remote monitoring of the patient at his regular environment and with minimal influence on his daily activities, by improving the patient's quality of life [3]. These systems are based on a network of sensors with ability to acquire the patient's physiological and environmental information and to transmit it to a receiver located at the surroundings. This nearby receiver can process the information and send it to some faraway health centre later.

The progress registered by the remote monitoring systems has been possible thanks to last technological advances as the development of new sensors and the use of wireless transmission technologies. On one hand, the sensors are developed with more reduced dimensions, intelligence and operation autonomy. This makes possible for the sensors to be placed on the patient's body or somewhere of his close environment. These devices are called *wearable* and *environmental sensors*. On the other hand, wireless technologies make easier the communication amongst all devices of the system. Short range technologies as WiFi, IrDA, ZigBee or Bluetooth can be used for the communication between the sensors and a receiver located near the patient. The transmission of information between this device and a faraway health centre can be achieved with large range technologies as GSM, GPRS or UMTS.

At present there are lots of companies and research projects that are working on the development of new wearable sensors and monitoring systems. Companies as CardioNet, Medtronic, Biotronik or Welch Allyn have systems for the ECG signal monitoring [4][5][6][7]. Some research projects that can be mentioned are CardioSmart, MobiHealth or HOLTIN [8][9][10].

This paper shows a global vision of the Bluetooth wireless technology and its use in the wearable remote monitoring systems. Special attention is paid to those characteristics of Bluetooth that make it an appropriate technology for being implemented in the acquisition sensors of the system, by allowing the short range communication between them and the nearby receiver.

The next section shows the main components of a remote monitoring system with special interest in the basic characteristics of the acquisition sensors that make it up. Next the different remote monitoring scenarios that can be distinguished according to the location of the patient are explained. The components involved in each

ISSN: 1727-1983

scenario, their characteristics and functions are also described. Bluetooth technology and all the aspects that make it a suitable standard for being used in wearable and environmental sensors are described and finally, conclusions are shown.

Remote monitoring systems and wearable sensors

As it has been said previously, a remote monitoring system performs the control of the patient's state through the acquisition, processing, transmission and/or storage of his biomedical and environmental data: ECG, blood pressure, temperature, position, etc. Moreover, this control is carried out while the patient remains at his regular environment doing his daily activities.

Any remote monitoring system consists of following elements [11]:

- A network of sensors which performs the acquisition of the patient's information: glucose level, ECG signal, weight, temperature, location, etc.
- A near bridge device or access point which carries out the communication between all the acquisition sensors and a faraway receiver.
- A faraway health centre like a hospital where the information belonging to a patient is received and analyzed by a specialist or health worker.

The appearance of new acquisition sensors and wireless transmission technologies has made the remote monitoring systems to progress towards the called "wearable" systems where the sensors are characterized by the following features:

- Reduced weight and size that allow the sensors to be placed on the patient's body and/or at some location of his surroundings.
- Low power consumption that allows long time continuous operation of the sensors. This feature plays an important role since these devices are supplied with batteries in order to ensure the mobility of the patient.
- Enough intelligence to carry out all the tasks (acquisition of information, communication with another sensor and the bridge device …) in an automatic way with no participation of the patient.
- Wireless communication ability that allows the exchange of data among all the sensors and the bridge device, by ensuring a total mobility of the patient while the monitoring process is being performed.

Acquisition devices with the features showed above are called *wearable* and *environmental sensors*. Both types of sensors have the same features and the only difference between them is the location where they are placed. In this way, the wearable sensors are worn on some part of the patient's body. The environmental sensors are placed generally at some location in the surroundings of the patient: furniture, bed, household appliance …

The use of wireless technologies in the wearable and environmental sensors offers a significant advantage compared with the wired ones. The elimination of troublesome wires makes possible to carry out the monitoring process and at the same time the patient's mobility is ensured. Short – medium range wireless technologies as WiFI, IrDA, ZigBee or Bluetooth are suitable for an efficient communication amongst the sensors and the bridge receiver since they have reduced power consumption for the coverage provided.

Remote monitoring scenarios

The use of wearable sensors in the remote monitoring systems allows the patient to be anywhere while his health state is being controlled. For this reason, several remote monitoring scenarios can be distinguished according to the location of the patient: *indoor*, *outdoor* and *intra-hospital monitoring*. The first scenario refers to the control of the patient at home while the second one includes all other situations where the patient is away from home; a theatre, work place or the street are some examples of the outdoor scenario. Finally, the intra-hospital monitoring concept is used when the patient (with total mobility) must remain in a hospital while is controlled. This monitoring situation can be considered as a particular case of an indoor scenario. The only difference between them is the number of devices that makes the system up.

Given that the patient has total mobility, changes of scenario can take place during all the monitoring process. For this reason the system must have enough intelligence in order to adapt itself perfectly to these changes and not to have influence on the patient' state.

Next the different monitoring scenarios and all the devices make them up are explained.

Indoor monitoring scenario

Indoor monitoring (also called home monitoring) is the name given to the control of a patient at his own residence. The main profit of this monitoring scenario is evident: any remote control process achieved at a comfortable and regular environment provides more real information about the patient, allowing a better analysis by a specialist. An example of indoor monitoring scenario is the called Intelligent Home [12] where multiple environmental sensors are placed at strategic locations in the residence: chairs, bed, glasses, household appliance, etc. The information provided by these sensors makes possible to know all the activities of the patient at any time.

Several elements and networks of devices can be distinguished in an indoor monitoring scenario:

- Personal Area Network (PAN): this network is composed of all the portable devices which acquire the patient's biomedical parameters.
- Body Area Network (BAN): all the wearable sensors placed on the patient's body make this network up.

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- Home Area Network (HAN): this network is composed of all the environmental sensors placed at strategic locations in the patient's residence.
- Access Point device placed at a fixed location in the residence that carries out the communication with all the BAN, PAN and HAN sensors in order to receive the patient's information. Later this information can be transmitted to some faraway health centre by means of wireless (GSM/GPRS, UMTS …) or wired (PSTN, fiber optic …) technologies.

Outdoor monitoring scenario

One of the main features of the new remote monitoring systems is the mobility provided to the patient while the control process is carried out. There are lots of places away from home (street, work place, theatre, etc) where the patient can be and the monitoring process must continue. For this reason, the indoor scenario is not the only one possible. Outdoor scenario is the name given to all the monitoring situations where the patient is away from home.

Several elements make an outdoor monitoring system up:

- BAN sensors which acquire the patient's biomedical information.
- Bridge device or gateway that receives the information acquired by the BAN sensors for a later retransmission to some faraway receiver.

Although the outdoor and indoor environments are based on similar elements, the nearby device (gateway and access point) that receives the patient's information has different features in each one. In an outdoor scenario, the gateway can not be placed at a fixed location because of the patient's mobility and it must be carried by him all the time in order to ensure the communication with the BAN sensors. For this reason, the gateway must be a portable device, as small as possible and with great operation autonomy. Among all the electronic devices with these features, PDAs and mobile phones seem to be the most suitable devices for being used as a gateway in an outdoor monitoring system. These devices are portable, of general use and user-friendly apart from being equipped with short range (Bluetooth, IrDA) and large range (GSM-GPRS, UMTS) wireless technologies.

Intra-hospital monitoring scenario

Although all the possible monitoring situations are included in the scenarios described above, the monitoring process carried out in a hospital can be considered separately.

An intra-hospital monitoring system has two main applications:

- The improvement of the present telemetry systems which can not be considered as wearable monitoring systems.
- Tracking of patients in order to know the time spent by them in every place and service (waiting room, cardiology, etc). Later analysis of this information can provide new health service models and the improvement of the medical care.

Anyway, the intra-hospital monitoring scenario can be considered as a particular case of the indoor environment. The system consists of a BAN network located on the patient's body and several environmental sensors (mainly location detectors) which transmit the biomedical and location information to an access point device. However, as the hospital is a more extensive environment than a house, several access point devices must be placed throughout the hospital, each of them with a specific coverage zone.

Bluetooth and remote monitoring scenarios

Bluetooth is a short range wireless technology intended to replace the cables connect portable and/or fixed electronic devices [13-16]. Some key features are robustness, low complexity and cost, data rate, low power consumption and interoperability. These features allow Bluetooth to be used in multiple applications and sectors, included the Telemedicine. Medical devices as wearable and environmental sensors can make use of Bluetooth technology for the transmission of patient's information to some near receiver.

The basic concepts of Bluetooth technology are explained in the next sections, with special emphasis in those features that make it a suitable technology for being used in the communication between the acquisition sensors and a gateway or access point.

Basic concepts

The Bluetooth standard was created in 1998 with the main goal of allowing the transmission of voice and data between near electronic devices. The standard is based on several hardware/software protocol layers, each one with specific functions and features, and the called *Profiles* in order to get total interoperability among devices from different manufacturers (see figure 1).

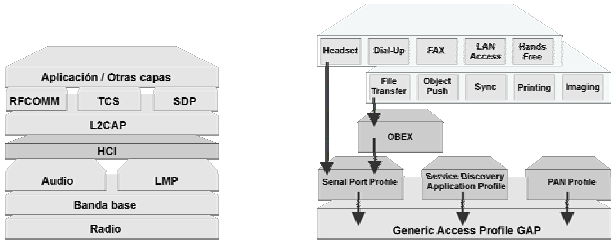

Figure 1: Bluetooth protocol layers and Profiles

Bluetooth operates in the unlicensed Industrial-Scientific-Medical (ISM) band at 2.4GHz. This makes Bluetooth a global standard and allows its use at any country. From a HealthCare point of view, a Bluetooth medical device can be used anywhere independently of

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the place where the device has been manufactured. The market advantages are significant: growth and competitiveness of companies, prices, etc.

However, using the ISM band also has a disadvantage: the interference level at any time can be elevated due to the great amount of devices that use this band. Frequency Hopping Spread Spectrum technique (FHSS) is used in order to combat these interferences. The physical channel is also time slotted and a Time Division Duplex scheme (TDD) is applied for full duplex transmission. In this way, each information packet is transmitted in a different time slot and hop frequency.

The establishment of Bluetooth connections between devices requires several procedures to be achieved:

- *Inquiry* procedure allows a device to know what devices are in its coverage range. This procedure must be carried out before establishing a Bluetooth connection.
- *Paging* procedure for establishing the connection.
- *Pairing* procedure for establishing a secure connection based on the knowledge of a PIN code. This procedure allows devices to be bonded.

Data rate

An outstanding feature of Bluetooth standard is the available data rate. Even though this depends on multiple factors (type of exchanged information, symmetry or asymmetry of the established link, role played by the Bluetooth device in the communication, etc), the standard allows a maximum data rate of 723.1Kbps. This value is enough for the transmission of any biomedical and environmental information acquired in a remote monitoring system. Two different situations can be distinguished with regard to the use of Bluetooth for the transmission of patient's information:

- The patient requires a continuous control of his parameters and the acquired data are real-time transmitted. Basic acquisition parameters as sample rate and resolution of the analogue to digital conversion (which depend on the type of information) establish the required data rate for the Bluetooth transmission. In this way, for example, a data rate of 192Kbps can be needed for the transmission of 12 lead ECG signal acquired with a sample rate of 1000 samples/sec. and a resolution of 16 bits.
- The patient doesn't require a real-time monitoring process because the acquired information is a parameter (temperature, blood pressure, weight, etc) whose value must be transmitted only at concrete times or a biomedical signal stored temporarily for a later transmission. In all these situations the patient's data can always be transmitted and the Bluetooth data rate has influence exclusively on the transmission time. This is the case of cardiac event monitoring by means of electronic Holter devices. These devices store the cardiac event in some type of non-volatile memory for a later transmission to a receiver.

Power consumption and coverage

Bluetooth technology has been developed for being used in portable devices supplied with batteries as mobile phones, PDAs, headsets, etc. Low power consumption is required in all these devices in order to get a long time continuous operation. Bluetooth makes an efficient use of the transmission power in two different ways:

- Several types of Bluetooth devices are distinguished according to the transmission power. Table 1 shows the Bluetooth devices, the transmission power and the coverage range of each one.
- Several low power modes (PARK, SNIFF and HOLD) where a device can be put are defined.

Table 1: Class of Bluetooth device

Class of device	Power	Coverage
I	20dBm	100 meters
II	4dBm	10 meters
III	0dBm	0.1 meters

With regard to the power consumption, Bluetooth is one of the most suitable technologies for being used in wearable monitoring systems if it is compared with others wireless technologies. Both a WiFi device and a Bluetooth class I device have similar power consumption but the WiFi one has a bigger coverage range that justify its no choice. As it'll be explained later, the coverage ranges required in most of remote monitoring cases (where all acquisition devices are near each other) can be provided by Bluetooth class II devices. Moreover, short coverage ranges make the monitoring systems to have higher security levels. Others wireless technologies as IrDA or ZigBee, even though they have smaller power consumption than Bluetooth, they have some features that don't make them suitable technologies for this type of systems. In one hand, IrDA is not a technology with omnidirectional transmission characteristic and a direct vision between devices is needed for carrying the communication out. On the other hand, ZigBee has a maximum data rate of 250Kbps that is not enough for the transmission of specific biomedical information.

The coverage range is another important factor when the use of Bluetooth in the remote monitoring systems is considered. In many situations the communication between the sensors and the gateway or access point device (which are placed close to the patient) can be achieved with Bluetooth class II devices. If the application requires a bigger coverage range, Bluetooth class I devices or more sophisticated networks can be used. An example of this situation can be the intra-

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hospital monitoring scenario (see section III). In this case, the use of additional access point devices located through the hospital provides a total monitoring process but requires more complex network infrastructures and more coordination among all the access point devices.

Bluetooth networks

Bluetooth allows devices to establish two different types of communication network: *piconet* and *scatternet*. A piconet is made up of all devices which exchange some type of information thanks to they are in the same coverage range and use a common communication channel (a common hop frequency sequence). A device can play two different roles in a piconet: *master* and *slave*. The master device initiates the communication with the rest of devices and manages the channel in order to get an efficient exchange of information. All devices that communicate with the master play the role of slaves. The basic structure of a piconet is shown in figure 2.
The scatternet is a Bluetooth network structure with more extensive coverage range than a piconet (figure 2). This type of network consists of several piconets which are interconnected by means of common slave devices.

From a network point of view, there is a clear correspondence between the elements that make a piconet up and the monitoring devices (BAN, PAN, HAN sensors and the nearby receiver). Figure 3 shows this correspondence in an indoor monitoring scenario.

Three Bluetooth networks can be distinguished in this environment:

- BAN piconet made up of the wearable sensors and the access point.
- HAN piconet made up of the environmental sensors and the access point.
- PAN piconet made up of the portable devices and the access point.

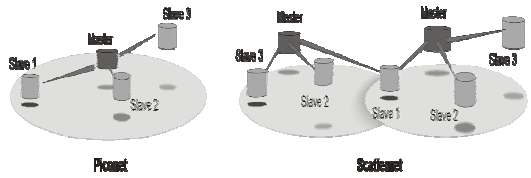

Figure 2: Piconet and Scatternet networks

In all these piconets the access point always plays the role of master and establishes connections with the slave sensors in order to receive the patient's information. However, the sensors can also establish connections with the access point if they have data for being transmitted. In this case, once the Bluetooth connection has been established, the roles played by the devices are exchanged and the access point becomes the master again.

A similar correspondence between Bluetooth and monitoring networks can be found in the outdoor and intra-hospital scenarios. An outdoor monitoring system requires a simpler network infrastructure since there is a BAN piconet exclusively made up of the wearable sensors and the gateway. However, if the monitoring process is carried out in a hospital a more complex network is needed due to the great amount of access points that can be placed through the environment. In this case, a piconet can always be established between the sensors and the access point closest to the patient.

Another feature of the Bluetooth technology is the ability for establishing ad-hoc networks which need neither a specific infrastructure nor an administrator device. This makes all the required procedures in order to establish a Bluetooth network to be performed by the monitoring devices without participation of the patient. This makes easier the monitoring process and improves the patient's quality of life.

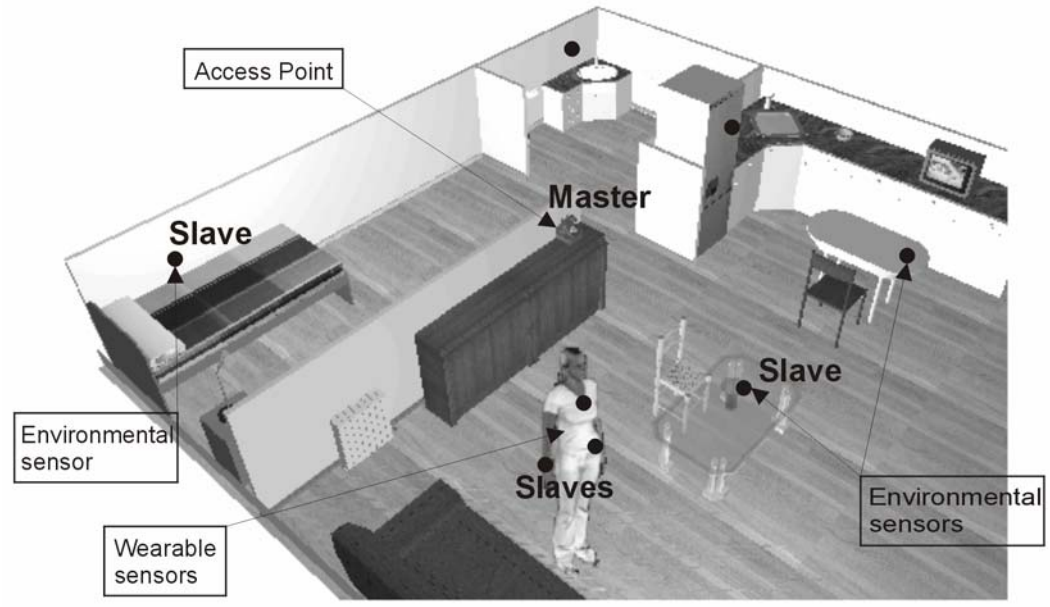

Figure 3: Indoor monitoring scenario

ISSN: 1727-1983

Security

Security and privacy are basic aspects in any remote monitoring system since medical and personal information is being acquired, processed and transmitted. Bluetooth provides several security methods and levels:

- Device authentication by means of the pairing procedure for the establishment of secure connections.
- Encryption of the information exchanged between devices.
- Short coverage range that prevents intrusive devices from cutting off the communications.

The communication between the acquisition sensors and the near receiver is carried out in a reduced and close to the patient environment. The short coverage range provided by Bluetooth reduces the likelihood that an intrusive device could get the patient's information. If an intrusive device is located in the coverage range all the Bluetooth security and encryption mechanisms start.

Bluetooth has some advantages if it's compared with others wireless technologies. WiFi technology has a bigger coverage range than Bluetooth and this allows intrusive devices to cut off the patient's information without the necessity of being close to the monitoring environment. IrDA technology is not also a suitable technology since it requires direct vision between devices for carrying the communication out.

Conclusions

From the previous sections and the experience acquired by the authors of this paper it can be deduced that Bluetooth is a suitable wireless technology for being used in the remote monitoring systems.

Bluetooth technology can be used in any medical and monitoring device due to its standard and interoperability features, by ensuring a perfect operation anywhere.

Data rate, power consumption and coverage range are basic features in order to justify the suitability of the Bluetooth technology. In one hand, the data rate allows Bluetooth to be used for the transmission of any biomedical information. On the other hand, the coverage range of Bluetooth class II devices is sufficient for covering the extension of the monitoring networks (BAN, PAN and HAN). Moreover, the Bluetooth technology can be implemented in wearable and environmental sensors supplied with batteries thanks to the use of low transmission power and several low power modes.

Another aspect of interest is the Bluetooth networks, their characteristics and the role that a device can play in these networks. The ad-hoc feature in the Bluetooth networks allows devices to establish and control the communications amongst devices in an easy way. Moreover, it is clear the identification between the monitoring devices in the BAN, PAN and HAN networks and the elements that make a Bluetooth piconet up. Moreover, the ability of the Bluetooth technology to control and manage the processes involved in a communication (inquiry procedures, connection establishment, etc) allows the remote monitoring system to control the patient' state without his participation.

Security plays an important role in the remote monitoring systems because personal information is being processed. Bluetooth provides several security and encryption mechanisms which allow a device authentication before the establishment of the connection and the encryption of all the data exchanged between devices.

Acknowledgments

This work was supported by projects G03/117 from Fondo de Investigaciones Sanitarias (Spanish Government) and 41/2003 from Departamento de Salud (Navarra Regional Government) and a personal grant to Miguel Galarraga from Departamento de Salud (Navarra Regional Government).

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ISSN: 1727-1983