A Wireless Sensor Network Infrastructure for Personal Monitoring

Aitor Arriola[#], Steven Brebels[Δ], Daniel Valderas[○], José M. Blasco[*1], José F. Hernández[*2], Eduardo Montón[*3]

[#]*Ikerlan, Apdo. 146, Pº. J. Mª. Arizmendiarrieta, 2, 20500 Arrasate-Mondragón, Gipuzkoa (Spain)*

aarriola@ikerlan.es

[Δ]*IMEC vzw, Kapeldreef 75, B-3001 Leuven (Belgium)*

brebels@imec.be

[○]*CEIT and Tecnun (University of Navarra), Manuel de Lardizábal 15, 20018 San Sebastián (Spain)*

dvalderas@ceit.es

[*]*TSB Soluciones, Ronda Auguste y Louis Lumiere, nº 2,3 local 13, Parque Tecnológico de Valencia 46980 Paterna, Valencia (Spain)*

[1]jblasco@tsbsoluciones.es

[2]jhernandez@tsbsoluciones.es

[3]emonton@tsbsoluciones.es

***Abstract*— This paper presents an infrastructure for the deployment of personal applications, based on the monitoring of the users in an unobtrusive way, independently of their location and activities.**

The infrastructure is based on the ZigBee technology, which allows the deployment of a mesh network. This network is formed by fixed and mobile nodes, making it possible the transmission of data acquired by sensors integrated in both the fixed and mobile nodes. The infrastructure also provides a mobile device that allows a continuous monitoring, even if the user is outside the coverage of the fixed network.

The design and development has been performed taking into account and giving solutions to the main issues of this type of technologies: size, power consumption, body antennas and mobility of nodes.

Finally, two applications developed upon this infrastructure are described: an advance teleassistance application, and a Body Area Network for sleep disorders monitoring.

I. Introduction

This paper describes a proposal of a Wireless Sensor Network Infrastructure for personal monitoring of users during their normal daily-activities.

The proposal is based on the well-known concept of Wireless Sensor Network [1], which provides the possibility of wireless and unobtrusive connection of body and ambient sensors for the monitoring of the personal health of the user, but taking into account all the difficulties of the deployment of this technology regarding power consumption, size, batteries, body antennas, etc.

The infrastructure makes use of both star and mesh topologies in order to make it possible the monitoring of the user in indoor and outdoor places.

Section II of this paper describes the concept of Wireless Sensor Network and its two main topologies: star and mesh topologies.

Section III describes briefly the technology used by the authors for developing and deploying the wireless sensor network infrastructure.

Section IV describes the proposed infrastructure focusing in its three main components: fixed wireless sensor communication network, mobile personal device, and mobile sensor node.

Section V describes several pHealth applications that can be developed over the presented infrastructure.

The paper finishes with the conclusions and the future work to be performed, in section VI.

II. Wireless Sensor Networks

A Wireless Sensor Network (WSN) is a network based on wireless communication technologies consisting of spatially distributed autonomous devices using sensors to cooperatively monitor physical or environmental conditions. The most important topologies used in this type of networks are the star and the mesh topologies.

A. *Star Topology for Sensor Body Area Network*

The star topology is a point-to-multipoint topology formed by a central network coordinator which connects and coordinates the rest of nodes of the network, which include the sensors. This topology is widely used in Body Area Networks (BAN) for monitoring physiological parameters with sensors located in different parts of the user's body.

B. *Mesh Topology Sensor Network*

The network is composed by nodes placed around a limited space, which act as routers, in order to transmit the information generated by sensors to a gateway or drain node. Sensors are integrated in some of the network nodes to acquire the data. These networks are useful for monitoring parameters of the ambient, environment and behaviour of the user in a determinate place, for example at home.

III. IEEE 802.15.4 AND ZIGBEE AS A WIRELESS SENSOR COMMUNICATION TECHNOLOGY

Wireless Sensor Networks show specific requirements for the physical layer, such as low data rate, energy efficiency, and robustness. The standard IEEE 802.15.4 [2] covers all these aspects. This standard describes a low data rate WPAN solution that can enable applications requiring multi-month to multi-year battery life with very low added complexity, operating in an unlicensed, international frequency band. This makes it very suitable as a sensor communication technology.

From the network point of view, Wireless Sensor Networks require scalability, reliability and self-configuration. The most suitable network topology to achieve these goals is the *mesh* topology. Nowadays there is not a unique standard for mesh networks. Most of the solutions in the market are based on IEEE 802.15.4 (such as ZigBee [3], TinyOS, DUST, Arch Rock, Crossbow or MillenialNet), while there are also companies who have developed full proprietary solutions (such as Z-Wave, Insteon, NanoNET, Mesh Scope or En Ocean). ZigBee, Z-Wave and Insteon have created their own alliances to strengthen their market position. For the ZigBee Alliance, its membership currently stands at more than 250 companies.

The solution presented in this work uses the IEEE 802.15.4 standard for physical and MAC layers, and it relies on ZigBee for the top communication layers. A brief description of both will be done.

The IEEE 802.15.4 physical layer uses spread spectrum techniques (DSSS), and it comes in two versions: one designed to operate in the 868 MHz (EU) and 915 MHz (US) ISM bands, and the other designed to operate in the 2.4 GHz global ISM band. The lower frequency band utilises BPSK modulation to achieve data rates of 20 kbps (EU) over a single channel and 40 kbps (US) over 10 channels. The higher frequency band utilises O-QPSK modulation to achieve a data rate of 250 kbps over 16 channels. The IEEE 802.15.4 MAC layer supports star and peer-to-peer topologies, giving flexibility for the application. Each PAN has exactly one PAN coordinator and other devices may associate or disassociate at will.

The ZigBee Alliance addresses the higher layers of the communication stack from the network layer to the application. Therefore, the ZigBee protocol will address the network layer, the application support sub-layer, the ZigBee device profiles, the ZigBee device objects, the application framework and a set of application profiles.

The network layer provides a hybrid tree/mesh topology, which extends the range of IEEE 802.15.4 and incorporates device discovery. The application support sub-layer provides mechanisms to create binding links between devices to simplify the communications. The ZigBee device profile, describes the operation of each type of device supported by ZigBee: a ZigBee coordinator, a router and an end node. The ZigBee device objects provides the building blocks used by the ZigBee device in order to accomplish certain tasks within a network, for example as service discovery. The application framework describes how to build an application profile in such a way that it conforms to the rules of ZigBee and ensures interoperability. Finally, the application profiles define how each type of device operates.

IV. WIRELESS SENSOR INFRASTRUCTURE

The proposed infrastructure is based on three different parts:

- *Fixed Wireless Sensor Communication Network*: this infrastructure is composed by fixed nodes that are in charge of routing the data acquired by sensors to a gateway or drain node. These fixed nodes are thought to be included in the home of the user and have the capacity of including ambient sensors to monitor parameters dealing with the user's environment.
- *Mobile Personal Device*: it can be a PDA or a mobile phone including a SD adaptor module with the capacity of connecting wirelessly with the fixed infrastructure or forming a Body Area Network with several mobile sensor nodes.
- *Mobile Sensor Node*: this node is designed in order to be able to send data acquired by a body sensor attached to the node. The node can transmit the data to the fixed wireless network or to the Mobile Personal Device. The module has been developed in order to be able to transmit the information to the fixed infrastructure even if the user is in mobility. The communication with the Mobile Personal Device makes it possible the transmission of the data in a Body Area Network, allowing to monitor the user although he/she is not in the coverage of the fixed infrastructure.

The combination of the different parts (or some of them) provides a base infrastructure for the monitoring of the user during his/her normal life in an unobtrusive way. Some possible applications are described in the section V of this document.

Below, a more detailed explanation of each module is provided.

A. Fixed Wireless Sensor Communication Network

The function of the fixed wireless sensor communication infrastructure is to provide a network to transmit the data acquired by the sensors to a gateway or drain node.

For this objective, a network formed by a mesh of nodes has been developed. These nodes are based on the System of Chip (SoC) CC2430 of Texas instruments. It includes a microcontroller (8051) and a RF transceiver (CC2420) that implements the stack of the IEEE 802.15.4. At network level, the Z-Stack provided by Texas Instruments has been used, which allows the deployment of a mesh network following the ZigBee specification.

Regarding the power supply, the nodes are designed to be plugged into the mains, since they are thought to be included in buildings as homes, residences, hospitals, etc.

Necessary ambient sensors in an application should be connected or integrated to the nodes, in order to provide data.

The main problem of a whole wireless network based on ZigBee specification is the limitation of 250 kbps. This general capacity of the network can be insufficient in some applications, specially if there are several sensors that provide high-sampling data (e.g. physiological sensors to acquire ECG, EEG, etc).

This problem is being approached taking advantage of the fact that the fixed nodes are plugged into the mains. For this reason, it is possible to use Power Line Communication (PLC) to route data from the sensors to the gateway, extending the communication range without the need of additional wired infrastructure. This way the 250 kbps are not shared by the whole wireless mesh network but each fixed node provides an access point to the network with 250 kbps capacity. Broadband PLC (UPA, HD-PLC or HomePlug) permits rates up to 200 Mbps.

B. Mobile Personal Device

The Fixed Wireless Sensor Communication Network provides a network that allows the monitoring of parameters in a determinate area. In addition, this network can be deployed only if the area fulfils some requirements (usually inside places with power supply network). A lot of the daily-activities of the users to be monitored are outdoors. However, body sensors (see next sub-section C), made to acquire physiological signals, can transmit the data to the fixed infrastructure only when the user is inside the coverage of the network.

In order to make it possible to monitor these body signals in situations out of coverage from the fixed network, we have developed the SD card adaptor (based on the SoC CC2430) shown in Fig. 1. It can be included in a PDA or mobile phone in order to provide a Mobile Personal Device. This device can act as central coordinator in a Body Area Network receiving the data from the body sensors.

In addition, the Mobile Personal Device can work as a mobile node inside the coverage of the fixed infrastructure.

Fig. 1 SD card adaptor

C. Mobile Sensor Node

The last module of the infrastructure is the Mobile Sensor Node. This module is designed to include body sensors that allow the monitoring of physiological parameters. It also can be programmed to provide data related with the user like identification, allergic problems, prescribed medicine, etc.

The Mobile Sensor Node, shown in Fig. 2, has been designed to be as small as possible, and it is based in the same SoC CC2430 used in the rest of modules of the system.

This is the module with the most demanding restrictions in design and development, because it should fulfil the next characteristics:

- *Small size*: the module should be as small as possible since it is thought to be integrated with sensors placed in the body of a person. The bigger the final device, the more obtrusive the system is for the user.
- *Power Consumption*: the module is thought to include a battery for power supply. The battery will depend on the final integration with the sensor. Batteries can increase importantly the size of the module if this consumes a lot of power. The system has been designed in order to consume very little power, specially in the transmission of data with low frequency (every few seconds), when it will be necessary only a coin battery, as it is explained below.
- *Antennas*: the use of the sensors integrated with the module places the antennas in close contact with the human body, which implies a strong attenuation of the signal when propagating through the body. As it is explained below, this issue has been taken into account in the design of the module.
- *Mobility*: the inclusion of mobile modules like the Mobile Sensor Node in a mesh wireless network based on ZigBee is not trivial, as it is necessary an important quantity of exchange of information in the management of this network. This issue is also explained deeply below.

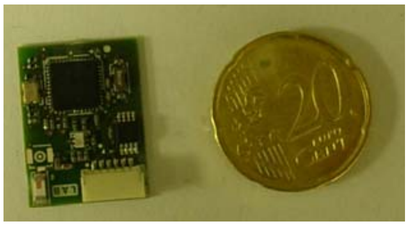

Fig. 2 Mobile Node electronic board

1) Power Consumption:

Low power consumption during communication is one of the strongest requirements for a wireless sensor node. In order to achieve this, the node has to stay in *sleep* mode for most of the time, waking up periodically only to send the value of the physical parameter it is sensing. The 802.15.4/ZigBee chips in the market (e.g. CC2430 by Texas Instruments, EM260 by Ember, or MC1321x by Freescale) provide sleep modes in which the chip consumes less than 1 μA. However, power consumption in RF transmission and reception can be between 20 and 40 mA, depending on the chip. An average value of 27 mA can be considered for the chip used in the present solution (CC2430). In Fig. 3 we can see a more detailed time variation obtained in measurements.

It must be noted that low power has to be considered not only for the communication part of the node, but also in the sensor and its conditioning, as well as in the application.

Normally, lithium–manganese dioxide cell batteries (3V) are used in wireless sensor nodes, due to their high capacity, small size and relatively low cost. These batteries are suited for applications which require continuous small currents, with additional peaks around 10-20 mA. The most usual formats are CR2032 and CR2432, with a nominal capacity of 230 mA and 620 mA, respectively. The solution presented in this work uses a CR2032 battery.

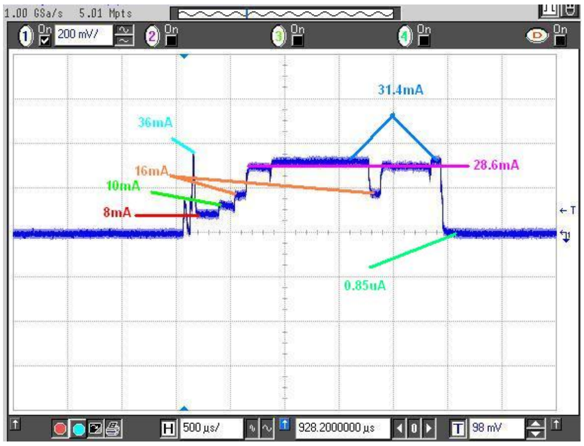

Fig. 3 Time variation of the current consumption for a CC2430-based node

It should be highlighted that current peaks have a big impact on battery lifetime. There are two phenomena related to current peaks on batteries: depolarization and reduction of capacity. It has been found on measurements that the nominal capacity of a battery can be reduced from 20% to 50% (depending on the type of battery) in an application with sleep-to-normal-mode transitions.

2) Antennas:

In Wireless Sensor Networks for Body Area applications, antennas are placed in close contact with the human body. This means that the presence of the human body in the near field of the antenna has to be taken into account from the first steps of the design. In this section, an overview will be given about the issues involved when designing Body Area Network antennas.

At frequencies of a few GHz, the penetration depth of waves in human tissues is close to 100 mm [4]. This implies that they will be strongly attenuated when propagating *through* the body, while communication *around* or *out of* the body will still be feasible. For design purposes, a three-layer body model consisting of skin, fat and muscle layers can be used [5]. Electrical parameters (dielectric constant and loss tangent) of these layers can be found in [4], where we can see that human tissues show very high electrical permittivity and losses. In [6] we can also see the range of variation in the size of these tissues. For the present work, the following properties and dimensions will be used:

TABLE I
BODY MODEL PROPERTIES

Tissue	Thickness (mm)	Dielectric Constant	Loss Tangent
Skin	0.6	38	0.28
Fat	0.4	10.8	0.18
Muscle	20	52.7	0.24

In order to show the impact of the human body on antennas, two distinctive planar antenna topologies have been modelled: a CPW-fed Inverted-F Antenna (IFA) [7] and a microstrip-fed patch antenna [8]. The first one is made on one metal layer, while the second one has an additional ground plane which will act as a shielding layer, as will be shown later. A 1.6 mm-thick substrate with dielectric constant 3.1 and loss tangent 0.01 has been used. Fig. 4 and Fig. 5 show the modelling results, obtained on Ansoft HFSS, for the matching, radiation pattern and efficiency of these antennas, with and without the human body.

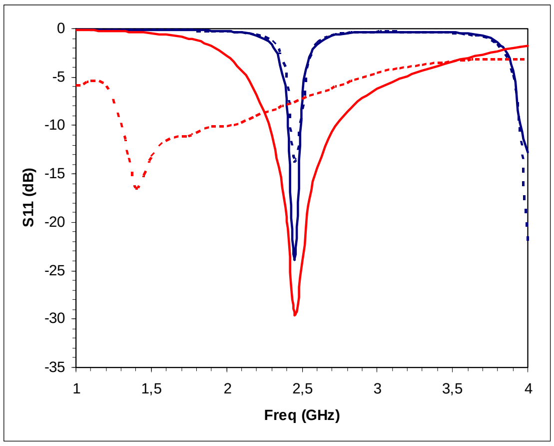

Fig. 4 S11 simulations for patch antenna (blue) and IFA antenna (red) for free-space (solid) and on-body (dashed) operation

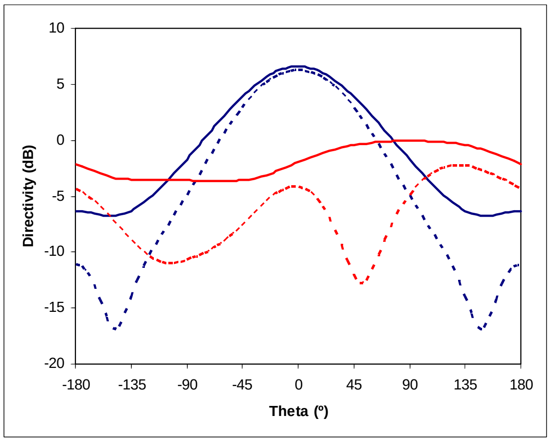

Fig. 5 H-plane directivity for patch antenna (blue) and IFA antenna (red) for free-space (solid) and on-body (dashed) operation

TABLE II
SIMULATED EFFICIENCY RESULTS

Simulation model	Efficiency of Patch Antenna (%)	Efficiency of IFA Antenna (%)
Free-space	72	97
On-body	54	4

We can see that the shielding layer of the microstrip antenna prevents detuning, efficiency drop and pattern distortion. However, an antenna with a shielding layer becomes more directional, and that could not be desirable for certain BAN application. For the IFA, mismatch can be improved by redesigning the antenna on the body model, and the efficiency can be increased inserting an air-gap between the antenna and the body, although the solution becomes less compact.

On-body measurements have also been performed with two commercial antenna prototypes: a Planar IFA (PIFA) with ground plane, and a printed monopole antenna. These measurements confirm that antennas with shielding layer, such as the PIFA, are more immune to detuning (see Fig. 6).

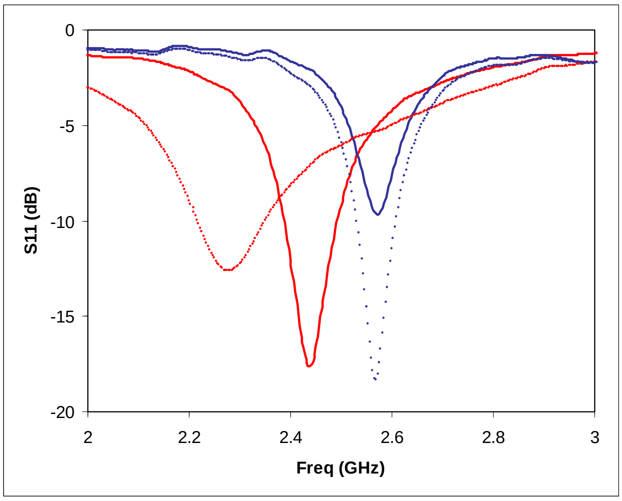

Fig. 6 S11 measurements for PIFA (blue) and printed monopole (red) for free-space (solid) and on-body (dotted) operation

For the Mobile Personal Device and the Mobile Node for Personal Monitoring, a ceramic antenna from Johanson Technologies has been selected (part number 2450AT18A100), as compact size has been the most relevant issue. This is an electrically small antenna with omnidirectional radiation pattern, which therefore can be affected by the presence of the body. In the final prototype, a distance of approximately 5 mm has been kept between the body and the antenna, obtaining reasonable range performance for communications outside the body. However, the blocking effect of the body has been observed for links through the body, due to the low penetration of the waves at the selected frequency.

3) Mobility in the fixed infrastructure:

Maintaining a mesh network requires quite a high information interchange between all the devices in the network. In a star network all the devices know who the coordinator is and they transmit the information directly to it. However, in a mesh network, none of the devices forming the system knows when it will have to act as a router for another device. For this reason, each device shall stay at least a certain period of time listening to the channel in order to be able to provide this routing feature. This is not a problem for mains powered devices but for battery powered devices, aiming not to change or recharge those batteries during very long periods, each millisecond with the receiver turned on decreases its life.

For including non-router devices in mesh networks, father-child relations are established between these devices and routers. These relations require a lot of data interchanging, which affects also to the life of battery powered devices. If the mobile device does not move frequently this is not big issue, since this interchange will be performed few times, but for mobile devices moving continuously, the father-child method is not an optimal one.

In order to avoid this process each time the mobile device should change its father, the adopted solution has been to make each of the routing devices in the network think that the mobile device is its child, so that they accept any data coming from it, always maintaining compatibility with the chosen protocol. Supported by the location engine, so that the system knows the position of the mobile device, it is easy for the coordinator to determine who the actual father of this device is.

V. PHEALTH APPLICATIONS

A. Advanced Teleassistance

This application provides a home advanced Tele-assistance service using the infrastructure described in this paper. Concretely, the infrastructure has been deployed in this way:

- *Panic button and location wrist device*: device to be worn by the user, based on the Mobile Sensor Node. In this case, the Mobile Sensor Node has been adapted to transmit a ZigBee ID frame each 2.5 seconds, and it is provided of a button. The ID frame is used in order to locate the person at home, and the button can be pressed by the user if he/she has any problem.
- *Fixed Wireless Sensor Communication Network*: deployed around the apartment or the area being monitored, including a node in each room and forming a ZigBee mesh network. Each of the different nodes acts as a beacon, receiving the information sent by the wrist device, both ID frames and button panic frames. In the case of an ID frame, the infrastructure node adds the RSSI (Receiver Strength Signal Indicator), and resend all the frame to the network coordinator.

In this application, the network coordinator is based on a mini-PC architecture including a drain node of the fixed infrastructure which makes it possible the reception of all the data sent by the nodes. Using the ID frames plus the RSSI information, an algorithm calculates in which room the user is and can detect different risky situations (unusual prolonged stay in a room, unusual stay in room at certain hours of the day, etc.).

The detection of these risky situations or the pressing of the panic button by the user, active the transmission of a SMS message or an automatic phone call to a family assistant. Each of the beacon nodes contains a hands-free system, so that the assistant can contact the user wherever the network locates him.

B. Sleep Disorders Monitoring

At European R&D level, a lot of efforts are being made in the development of systems for monitoring sleep disorders. For example, in SENSATION project [9], several body sensors have been developed, in order to acquire different physiological parameters (ECG, EOG, heart rate, respiration rate). In addition, the work in SENSATION has been focused in the fusion of the different data to monitor the different sleep stages. During this project, a BAN [10] has been developed in order to concentrate all the data in a central coordinator, which is capable of communicating with an external system in a Local or Wide Area Network. In this case, the SENSATION BAN provides a specific central device, called PDPU (Personal Data Processing Unit), and generic Sensor Communication Modules (SCM) for the connection of the different sensors.

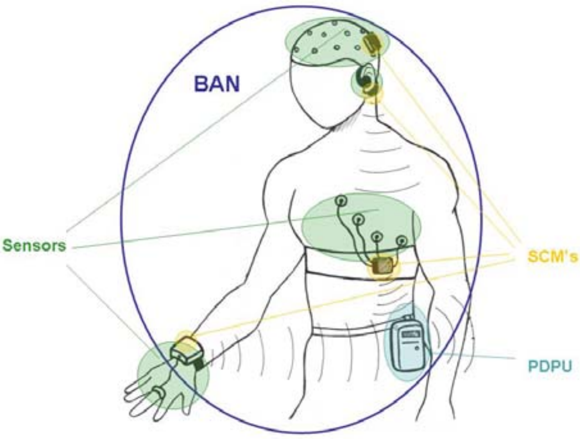

Fig. 7 SENSATION BAN Scheme

Fig. 8 SCM and PDPU modules of the SENSATION BAN

Current work is focused on improving this BAN capacity substituting the SCM by the Mobile Sensor Node for personal monitoring. This way, the different data acquired by sensors will be transmitted by the Mobile Sensor Node in two possible ways, depending on where the user is:

- If the user is inside the coverage of a Fixed Wireless Sensor Communication Network, for example deployed in the user's house or in a hospital with sleep laboratory, data will be transmitted directly to the network, being possible to manage the data where it is necessary.
- If the user is outside the coverage of the fixed network, for example, in the street, the mobile nodes will transmit the sensor data to Mobile Personal Device, forming a BAN.

This way, it will be possible to monitor users with sleep disorders during 24 hours, independently of their location and usual daily activities. They will be monitored in the most unobtrusive way, no matter where they are.

VI. Conclusions and Future Work

This paper presents a wireless sensor network infrastructure that allows personal monitoring of the user. For this objective different issues have been solved, that are implicit to the use of wireless sensor technologies like ZigBee.

The mobile sensor node has been designed and developed to have low power consumption and small size. It is very important the programming of the node depending on the attached sensor and the application, in order to minimize the power consumption in each case.

On the other hand, we can conclude that there is not an ideal solution for BAN antenna topologies. For each application, a trade-off between compactness, efficiency and desired radiation pattern has to be found. In the current solution, further characterization of the selected antenna in its final operating conditions could allow to optimize it for a specific platform or a specific location on the body. On the other hand, the blocking effect could be improved by placing communication nodes radiating outwards on both sides of the body.

We also have provided one solution for the mobility of the mobile sensor nodes in Zigbee mesh networks. In the future, it is necessary to work in the roaming between the mesh fixed network and the mobile BAN provided through the mobile personal device.

Finally, work is also being done to increase the capacity of the fixed wireless network using PLC in the backbone. A future work line is the use of the UltraWideBand wireless technology in the physical layer, as it can provide higher throughput with lower power consumption.

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