Proceedings of the 28th IEEE
EMBS Annual International Conference
New York City, USA, Aug 30-Sept 3, 2006

Design of antennas for a wearable sensor for homecare movement monitoring

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Abstract— **This paper is focused on the discussion of different trade-offs that frequently arise when selecting the appropriate antenna technology for a wireless sensor for home-care applications, and the implications that every decision represents for the overall design. In order to devise an optimum design strategy, the main methodological concerns are illustrated with the example of a wearable movement monitor. The selection of a suitable air interface is based on the comparison among different standards for low-cost, low-power wireless communication devices, and a patch antenna is designed from scratch. Results obtained by simulation show that this design meets all the requirements in terms of shape, size, antenna performance and cost-efficiency, validating the followed approach.**

I. INTRODUCTION

Current trends in macroeconomical figures of developed countries seem to agree that a variety of factors are challenging the concept of human well-being, and Health is one of the most threatened sectors. Several causes have been pointed out as key factors for this change of landscape, including globalization, population aging, migration fluxes, the change of the structure of the family unit, the incorporation of women to work, unemployment rates and even environmental issues. Due to globalization, the health sector is undergoing a transformation in terms of focus, access, human resource deployment and distribution, essential care, and technological advances [1].

In technologically advanced market economies with substantial government participation, in many of which the public sector is still accounting for 40% of Gross Domestic Product and over, economy analysts foresee a collapse of national insurance systems in 40-50 years due to the inversion of the population pyramid. Although the descent of birth rate has partly been compensated with immigration fluxes, the most pessimists only assess this collapse to occur with a delay of a decade or two with respect to the previous estimates. On the other hand, in the private sector, employers and other private purchasers of health care services find that the soaring cost of health insurance premiums poses a threat to their competitive position in an increasingly global market [2].

Whichever the business culture is, it is accepted that a new reorientation of health resources is unavoidable, with citizens playing a more active role in the process of health care delivery, and having a greater involvement in education for healthy life-styles. The progress of information and communication technologies has opened an era in which powerful communication channels diminish geographical, temporal, psychological, and cultural distances around the world [3]. Distributed diagnosis and home healthcare (D2H2) is becoming a response to health challenges, serving as a change of paradigm [4] and natural evolution of the centralized and overburdened healthcare model.

A myriad of applications based on homecare technologies are being developed worldwide, with the functions of personal health monitoring and surveillance, and aimed at filling the gap represented by the middle-space between patient/user and professional services. The huge advancement experienced by this promising market has been due, not only to the widespread deployment of high-performance communication infrastructures, accessibility to wireless and mobile networks or the adoption of standards for interoperability and networking, but also to the development of key technologies including micro- and nanoelectronics, biosensors, distributed computing or biosignal processing [5], which evolve in parallel to the latest discoveries in biomedicine (genomic, proteomic and upper levels). Hence, notwithstanding the importance of service provider centers in home tele-care systems, the local scenario or point of care (POC) plays a major role. Home area networks (HAN) and personal area networks (PAN) rely on the successful synergy of different technologies around a set of sensors.

The clear advantages of wireless sensors over the wired ones in terms of mobility, seamless operation and unobtrusive perception to the user, explain the popularity of these technologies. In a search conducted over the IEEE Digital Library[1], using “wireless sensors” as search term, from the 100 most updated references, 39 of them addressed routing protocols and energy efficient architectures, 17 papers dealt with the air interface, MIMO, ultrawide-band (UWB) or modulation and coding schemes, 12 to network management and scheduling, other 12 to diverse topics like synchronization, simulation, security or channel performance, 10 to applications, 8 to implementations, and only 2 devoted to antenna issues. The paradox represented by the last figure is evident if it is compared to the research volume on antenna theory and design. A possible explanation to this finding is

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This work is partially supported by Fundacion CITIC, C/ Marie Curie 6, Parque Tecnologico de Andalucia, Malaga 29590, Spain, under Grant 657/2005, by the Spanish National Board of Biomedical Research (Instituto de Salud Carlos III, Fondo de Investigacion Sanitaria), under Grant PI040687, and by the General Directorate of Research, Technology and Enterprising (Junta de Andalucia), under Grant TIC 314.

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that too often the antenna is given a secondary importance in the development of sensors for wireless PANs, and in many cases off-the-shelf solutions are accounted for, without a complete view of the sensor as a whole, but as a set of aggregated subsystems.

Factors like the shape or size of the sensor place important constraints to the antenna, and resourcing to a commercial product does not always represent an optimum solution [9]. On the contrary, the design of the radiating structure must be tailored to such kind of requirements. For this reason, while the main objective of this paper is to design an antenna for a wearable movement monitor and falling detection device, the emphasis is put in the methodological issues which let antenna theory meet the specifications of a required performance together with a global view of the implications that the selection of a particular antenna technology represent for the overall sensor and viceversa.

The paper is structured as follows. In the next section the movement monitor is presented, and the functional and physical requirements that incide on the selection of a specific antenna solution are derived. Afterwards the design for the particular study case is outlined, justifying why different alternatives are preferred against others. Section 3 describes the performance expected by the design, showing different results. Finally the paper ends with a conclusion and summary.

II. MATERIAL AND METHODS

Two of the target populations for the market of homecare technologies are the elderly and chronic patients, which by no doubt represent the highest expenditures for the health sector. Pain and impaired mobility are the most frequent complaints in the elderly. Impaired mobility causes fear of falling and falls, which represent a valuable risk and challenging trauma, with an important impact in the health, quality of life and the mortality rate of this population. The risk of falls is emphasized when suffering from different chronic pathologies like end stage renal disease, due to secondary effects on the deterioration of mobility.

A review of the state-of-the-art in falling-detection sensors is contained in [6], [7], showing that most of these devices are usually worn over belts or other wearable elements, and that the most complex analysis of accelerations is performed off-line using the data gathered by portable storage systems. The authors have developed a movement monitor based on a novel patented two-layer architecture, which follows the concept of knowledge-based telehealthcare. The monitor is constituted by an Intelligent Accelerometer Unit (IAU), based on a four-axis accelerometric system, which signals are processed and transmitted to a personal server by means of a PAN. The last device is referred to as PSE. Both elements belonging to the PAN are worn by the individual allowing the separation of the sensor from the peripheral elements that comprise the interface that is implemented into the PSE. The IAU has been conceived as a two-ways communication device, to be worn like an adhesive patch fixed to the back skin, at the height of the sacrum, very near to the body center of gravity. The communication between the movement monitor and the telehealthcare center is established through a Remote Access Unit (RAU) connected to a public telecommunication network. The rest of this work is focused on the IAU.

A preliminary analysis of a laboratory prototype was presented in [8], showing the benefits of the distributed processing architecture, and the capability of customization to user profiles. However the aim of this prototype was the validation of the functional model, and did not account for the impact of the RF transceiver and air interface on the IAU architecture. These issues are discussed next.

A. Selection of the appropriate wireless technology

The main requirements affecting the selection of the air interface of the IAU with the PSE can be summarized as follows:

- The IAU must be a wearable sensor, attached to the back as a skin patch.
- It should not require manual intervention from the user (only battery replacement).
- The use of standards for the air interface is advocated.
- The solution must be cost-effective, minimizing the cost to the end-user.

As a consequence, only planar or integrated (chip) antennas could be used. In addition, the antenna size must be as low as possible, and a short-range, low-cost, low-power wireless standard is preferred against a proprietary RF solution for radio communications.

Regarding the last issue, recent wireless sensors for PANs have been implemented following a wide variety of standards, including irDA [10], Bluetooth (IEEE 802.15.1) [11], UWB (IEEE 802.15.3) [12], Zigbee (IEEE 802.15.4) [13], WiFi (IEEE 802.11X), GSM-GPRS [14] or even multistandard. On the other hand, the use of RF transceivers with off-the-shelf components and FSK, OOK or ASK modulations is widely extended [15], [16]. Although the development time can be reduced in these cases, the lack of interoperability of proprietary solutions and limited scalability are two important drawbacks. Considering that infrared communication is usually unidirectional, and within the "line-of-sight", and that the bandwidth required by the IAU is very low [8], Bluetooth and Zigbee stand out against the other alternatives. Compared with Bluetooth, Zigbee supports a much larger number of nodes, variable network topologies, location awareness and a very low power consumption, at the cost of lower data rates [17]. Therefore we have selected Zigbee as the air interface for the IAU-PSE wireless link.

B. Design of the antenna

The IEEE 802.15.4 standard specifies the physical and media access control layers at the 868 MHz, 915 MHz and 2.4 GHz ISM (Industrial, Scientific and Medical) bands. The use of surface-mount integrated antennas for these frequency bands meets the requirement of size for the IAU. However, as the size of chip antennas is much lower than the wavelength, a planar antenna can yield a better performance in terms of radiation resistance and directivity. Chip antennas provide the smallest solution possible, but the size reduction comes at a cost both in performance and pricing [18]. In addition the low profile of a planar antenna can lead to a minimum cost, better reliability and capacity of adjustment, given the flexibility of its design.

The selection of a planar technology implies that the antenna will be the largest element in the IAU, determining the dimensions of the wearable sensor. For this reason, and considering that the aim is to obtain an omnidirectional radiation pattern, we will only refer to the design of a single element. There is a wide variety of planar antenna configurations, including dipoles, slots, rectangular and circular patches. Dipoles and slots will be discarded because a nearly squared geometry is preferred against a quasi-linear. In addition, feeding structures for these antennas are more complicated, requiring a balun. Circular disk antennas offer performance similar to that of the rectangular geometries. Circular patches tend to be slightly smaller than rectangular ones, but depending on the circuit-prototyping technology circular printing can be more intricate and time-consuming. A rectangular patch antenna has been selected for the IAU.

The design of patch antennas entails different trade-offs, being the substrate one of the most critical variables. Substrate thickness should be as large as possible to maximize bandwidth and efficiency, but not so large to risk surface wave excitation. Thin substrates have lower efficiency, smaller bandwidth and lower input impedance. As the dielectric constant (ϵ_r) rises, so does the resistance and surface-wave level, patch dimensions can be reduced accordingly, but efficiency and bandwidth are reduced too. Nevertheless, our choice has been driven by cost considerations. The price of a mass-produced printed antenna is directly related to the substrate and connector costs [19]. Traditional microstrip antennas use substrates such as PTFE, quartz and honeycomb for good radiation. However, the resulting substrate costs are too high for homecare applications. Epoxy/glass (FR4) is a widely used material for low-frequency and digital circuit boards. Its low cost, easy availability and ease of fabrication are its strengths. Its high loss tangent ($\tan\delta = 0.01$ typically) and relatively variable dielectric constant (in the range of 4.4-4.7) limits its usage to the lower microwave bands. Taking into account that a scale factor of about 2 can be applied to patch size compared with PTFE, a 1.5-mm height, 35-μm copper-thickness FR4 substrate has been used in our work.

Another design variable is the feed structure. Three alternatives are frequently implemented: probe feed, microstrip line feed with or without inset, and aperture-coupling. The first option is discarded as it is obviously a connector-based approach. Microstrip line feed is appropriate for one-side design; the feed transmission line and the patch are in the same plane, sharing the substrate. Microstrip feed design guidelines recommend a thin substrate in order to minimize surface wave excitation, what degrades patch performance, as commented above. In addition, in case an edge-feed approach is followed, with no inset, a $\lambda/4$-length line segment is required for impedance matching, what implies an increase of the overall circuit size.

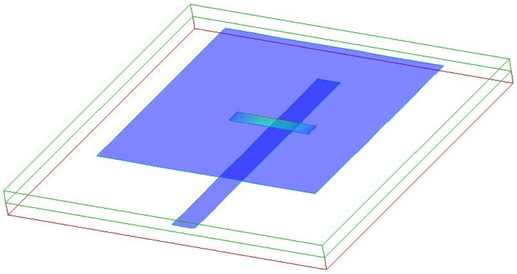

Fig. 1. Geometry of the patch antenna designed at 2.4 GHz

Aperture coupling was first proposed by Pozar [20]. The patch is etched as normal on a substrate. On the ground plane underneath the patch, a rectangular slot is opened. The feed line is on another substrate with the ground plane completely removed, crossing over the center of the slot and extending beyond it about $\lambda/4$ for impedance matching (feedline stub). This way the patch is completely shielded from the feed. In addition, this approach provides a better repartitioning of the IAU components for a desired size, since the accelerometers, microcontroller, wireless transceiver and feed line can be laid-out on the bottom substrate, while the antenna is placed on the top substrate, directly fixed to the adhesive patch. Moreover, different substrates can be used for the feed and radiator, providing more flexibility. However, due to cost considerations, the same FR4 laminate has been applied for the feed substrate in our design.

With regard to the patch size, antenna length must be about $\lambda/2$ for resonance condition. The patch width generally lies between about 0.5 to 2.0 times the length. A wider patch has lower input resistance, higher efficiency and a wider bandwidth. We have preferred a squared patch because its modification for circular polarization is easily attainable.

A preliminary design of a rectangular patch operating at 868 MHz was accomplished first, using approximate equations [21] and subsequent optimization with commercial EDA (Electronic Design Automation) software. The obtained dimensions were 8.11 cm (length) and 12.26 cm (width). While the simulated directivity is 6.4 dB, patch size is obviously over the maximum admissible dimensions. Besides, return losses were acceptable in a bandwidth of about 10 MHz only. The results of this study provided the arguments to increase the frequency to 2.4 GHz, which was finally selected. The geometry of the aperture-coupled squared patch is sketched in Fig. 1. Following the same procedure, the patch was designed first, at a frequency 2% over the desired resonance of 2.44 GHz (midband of Zigbee spectrum allocation), to account for the effect of the coupling feed, the slot was placed at the center of the patch, starting with a moderate length and a slot width about 0.1 times its length. Optimization variables were the square size, the slot length and width, and the feed length beyond slot center.

III. RESULTS

The dimensions corresponding to the optimum solution depicted in Fig. 1 were 27.7 mm for the patch side length,

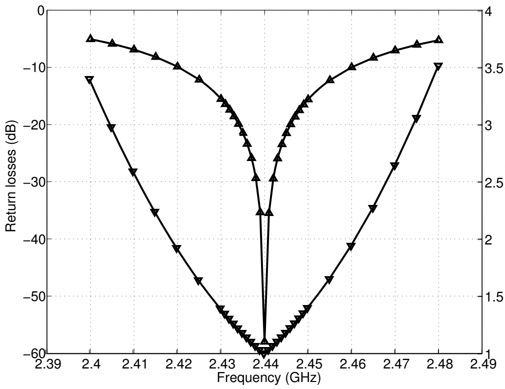

Fig. 2. Return losses (△) and VSWR (▽) of the squared patch antenna.

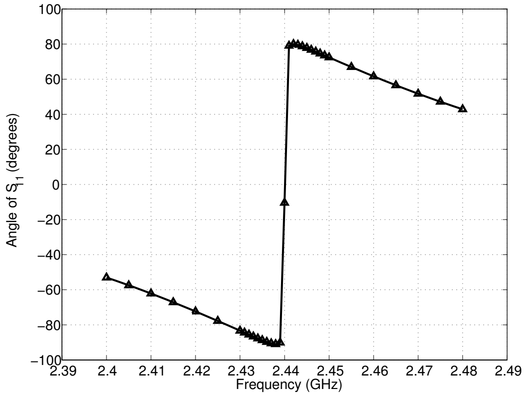

Fig. 3. Phase of the reflection coefficient at the antenna feed.

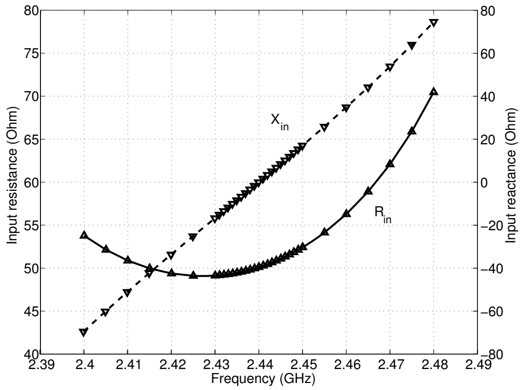

Fig. 4. Input impedance of the designed patch antenna. Solid line: real part. Dashed line: imaginary part.

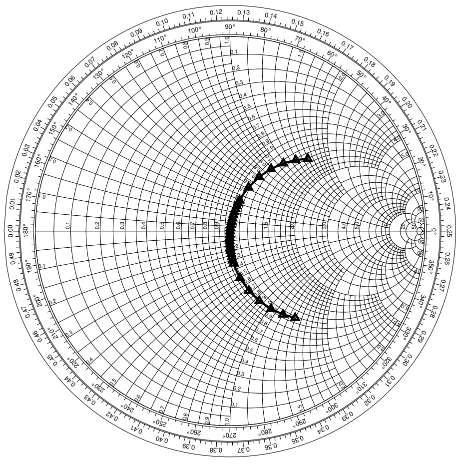

Fig. 5. Smith chart plot of the antenna impedance.

a feed line width of 2.8 mm, a slot length and width of 9.8 mm and 1.6 mm, respectively, and a feedline stub length of 10.7 mm. These dimensions are clearly compatible with a wearable skin patch IAU prototype.

The simulated performance of return losses is represented in Fig. 2, showing excellent impedance matching at 2.44 GHz and a bandwidth of over 40 MHz with VSWR < 2. The phase of the reflection coefficient at the antenna feed has been plotted in Fig. 3. Antenna impedance is represented in Fig. 4 to account for the real and imaginary parts, being evident the condition of resonance at 2.44 GHz and a nearly constant 50-Ohm radiation resistance in the 2.40-2.48 GHz range. Fig. 5 shows the same impedance in the Smith chart.

With regard to the radiation patterns, these have been depicted in the polar plots of Figs. 6 and 7, with the patch positioned in the X-Y plane and feedline aligned in X direction. The E-plane and H-plane correspond to cuts with azimuth of 0^o and 90^o, respectively. In both cases, the antenna radiates into an hemisphere, with a tiny back-radiation lobe due to the slot in the ground plane. However, the front-to-back ratio is over 20 dB, what makes radiation into the body back negligible.

The pattern is cuasi-omnidirectional in planes parallel to the patch and the direction of directivity is the Z axis, orthogonal to the sagittal plane and in back direction. The directivity of this antenna is 6.17 dB, but the gain reduces to 2.93 dB as a consequence of the drop of efficiency due to the dielectric losses of FR4 substrate. However, this is not a critical issue, since the PSE transceiver can be designed to radiate more power and with a higher sensibility. Finally, the main lobe beam width is 174^o.

IV. CONCLUSIONS AND FUTURE WORKS

This paper has been aimed at the design of an antenna for a wireless communication sensor following a methodological approach. As a result of the outcomes obtained in the previous sections, the following conclusions can be drawn. First, in spite of the fact that the design of wearable antennas has received less attention by homecare sensor developers than other issues related to the network management, the antenna has a great impact on the overall architecture of the sensor. Second, the selection of the air interface and antenna technology comport a variety of options which must be traded-off with the requirements of the sensor, being the simplicity, shape and size three important issues to account for. And third, the adoption of a standard air interface is highly recommended to ensure interoperability and a better scalability compared with proprietary solutions.

With regard to the antenna designed for the IAU, patch technology offers a better alternative than a chip antenna.

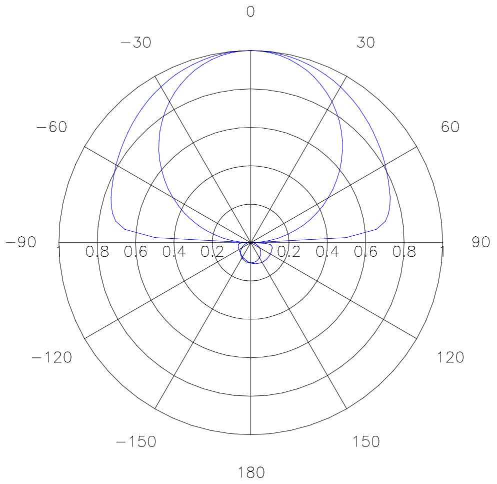

Fig. 6. Polar plot of the normalized radiation pattern. Outer trace: E-plane; Inner trace: H-plane.

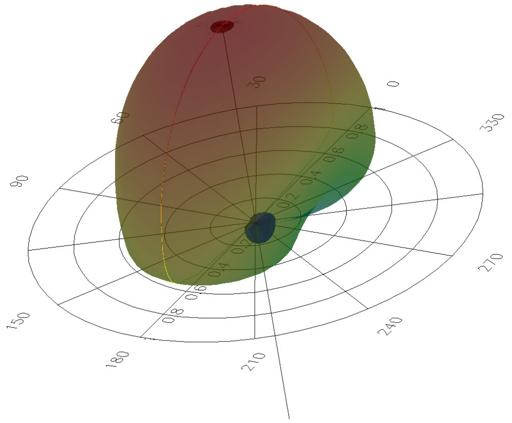

Fig. 7. 3D radiation pattern.

Performance obtained by simulation meets all the requirements of the IAU, representing a cost-effective solution. Future works in the antenna design will be focused on the measurement of the prototype to account for the impact of a finite-size ground plane and the effects of the patch cover, which could not be considered at design time. While the patch cover only produces a slight displacement of the resonant frequency, finite-size ground plane effects usually deform the radiation pattern, increasing the lateral and back-plane radiation as a consequence of spill-over. This effect should not be negative for our design, considering that the different options planned for the PSE (a bracelet on the wrist or a pendant on the neck) recommend some level of lateral radiation. Related to this, the perturbation to the patch shape for circular polarization will also be explored.

ACKNOWLEDGMENTS

The authors are grateful to the undergraduate students Juan Aguilar and José A. Perez for their assistance to this work.

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