An IPv6-enabled Wireless Shoe-Mounted Platform for Health-monitoring

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***Abstract*— An innovative wearable, partially self-powered, health monitoring and indoor localization shoe-mounted sensor module is presented. The system's novel shoe sole serves the double role of (i) medical-grade temperature probe for human body monitoring and (ii) renewable energy scavenger, which transforms the human motion to electrical energy. Mounted on the shoe is also an NFC reader for proximity-based localization purposes. An Adidas^{TM}-logo-shaped dual-band communication antenna is fabricated that exhibits great performance despite the close proximity to the high lossy human body. The proposed platform can be extended to other sensors applications, for example by embedding into the sole normal and/or shear force sensors in order to monitor the sport performances of the athletes as well as to improve the rehabilitation techniques.**

***Index Terms*— dual-band antenna, unobtrusive electronics, wearable electronics, RFID, NFC, health monitoring, WSN**

I. Introduction

The ever-increasing need for monitoring the the human health and the everyday physical activity more and more precisely prompts the researchers to investigate sensor technologies that are not only accurate but also power-autonomous and unobtrusive. The novelty of our proposed system lies into realizing concurrently these two goals with the development of a sensor- and energy-harvesting-enabled sole embedded into a shoe.

An innovative wearable, partially self-powered, health monitoring and indoor localization shoe-mounted sensor module is presented. The core of the system is the novel shoe sole that serves the double role of (i) a medical-grade temperature probe for monitoring of the human body and (ii) a renewable energy scavenger, which transforms the human motion to usable electrical energy through a piezoelectric transducer (PZT) and complements the compatible Li-ion rechargeable battery technology under a hybrid power system approach. Mounted on the shoe is also a tiny near-field communication (NFC) reader for proximity-based localization purposes. All the sensed information is gathered and pre-processed by a micro-controller unit (MCU) and relayed through transceivers of 900 MHz or 2.4 GHz or both that are connected to a single dual-band antenna. Special care has been taken so that this antenna does not only exhibit great performance despite the close proximity to the highly lossy human body but also assumes the ubiquitous and unobtrusive design of an Adidas^{TM}logo. The proposed architecture is shown in Fig. 1. The platform can be extended to other applications just by embedding new sensors: for example capacitive shear and/or normal force sensors embedded in the insole may be used to monitor the correctness of the sport activity for both professional and amateur athletes, as well as to have a feedback of the quality of physical exercise executed during a rehabilitation period after an injury.

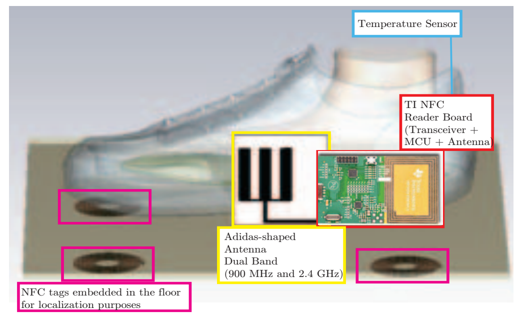

Fig. 1. Proposed architecture of the shoe-mounted sensor module.

II. Shoe-mounted Sensor Architecture

The proposed design is a combination of sub-systems, as seen in Fig. 1, able to work independently and to communicate the sensed information. The analog-to-digital converters of the MCU can measure the voltage of the voltage divider connected to a medical-grade thermistor. The same 5 cm by 8 cm sized board also houses an NFC reader chip that is used to detect the position of a person by illuminating a matrix of beforehand location-mapped NFC passive tags embedded into the floor tiles [1]. As opposed to using UHF-RFID technology, as proposed in [1], we move frequency-wise in this health-monitoring-related work to the lower frequency ISM band of 13.56 MHz. This magnetically coupled lower frequency field not only provides higher isolation from accidentally picking up tags mounted on nearby tiles but also eliminates any interference with the 900 MHz and 2.4 GHz dual-band Adidas^{TM}-logo-shaped antenna. The reader consumes no more than 120 mA of peak power and has with a nominal line-of-sight range of 12 cm.

The dual-band antenna is proposed to serve as the RF communication interface of the transceivers relaying health-and localization-related information to the surrounding wireless personal area network. The antenna has been designed to be aesthetically as unobtrusive as possible and has been fabricated on an organic substrate, i.e. regular photo paper, based on the direct transfer technique of inkjet printing with conductive silver nanoparticles, as shown in Fig. 2.

Fig. 2. Prototype.

A. Dual-band Adidas™-shaped Antenna

As previously stated, the antenna is realized based on the well known Adidas™-shoe-logo: the three stripes are sized in order to obtain a combination of monopoles. of $\frac{\lambda}{4}$ and $\frac{\lambda}{2}$ monopoles (the former for the 900 MHz frequency and the latter for the 2.4 GHz frequency). Compared to other antennas with a similar shape, as for instance the single-band E-shaped antenna reported in [2], the dual/triple-band M-shaped antenna presented in [3] and the dual-band fork-shaped antenna described in [4], in this case the design method is not to use the well known techniques to reduce the size of a patch antenna, but rather to properly size the elements as $\frac{\lambda}{4}$ and $\frac{\lambda}{2}$ monopoles. The 50 Ω matching has been obtained thanks to the properly-sized feeding line (front side of the substrate) and a ground plane printed on the back side of the substrate.

Figure 3a demonstrates the excellent agreement and performance of the simulated and measured return loss curves of the dual-band antenna for both 900 MHz and 2.4 GHz bands. Moreover, Fig. 3b shows very good results in terms of radiation pattern and gain (higher than 7 dBi) even considering the presence of the human foot. For brevity reasons, only the 900 MHz band is shown.

B. Energy Harvesting

Thanks to the low-power technologies implemented, the entire shoe-mounted sensor system can be powered by a hybrid power system that intelligently couples the compatible and very popular technology of rechargeable Li-ion batteries with a renewable energy scavenger. In particular, a flexible and as a consequence comfortable

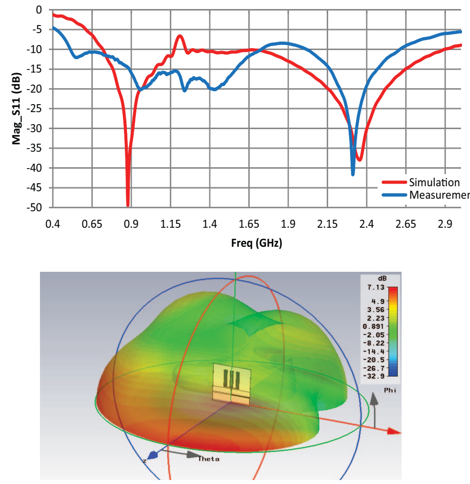

Fig. 3. a) Comparison between simulated and measured return loss curves of the antenna; b) Simulated Adidas™-shaped antenna radiation pattern at 900 MHz (with CST).

(differently from the push-button used in [5]) PZT, is embedded into the sole generating power step by step [6].

Because of the high unregulated output voltage of the PZT (100 ÷ 120 V) a circuitry has been implemented in order to power the system with 3.3 V (Fig. 4). The same figure shows the adopted circuitry diagram to rectify the voltage generated by the PZT and regulate it: the harvested energy can be stored on the input or the output capacitor. A dedicated pin to drive the microprocessor is also provided by the regulation block.

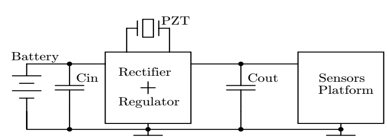

Fig. 4. Energy harvesting circuit diagram.

C. Localization and Sensors

For indoor localization purposes, an NFC system is used to detect the position of the person moving within a building. The floor is mapped with the help of a matrix of NFC passive tags, which are placed under the tiles and each has its own unique identification number.

On each step the small shoe-mounted NFC reader establishes communication with the NFC tag of the corresponding tile and extracts the unique ID of the tag. The correlation of this ID number with the real, absolute or relative, position of the human is easily achieved based on a previously stored look-up table where the NFC IDs are mapped to the real physical locations of the tiles. This location information, along with the medical-grade temperature of the human object, can be transmitted to an Internet-based service, as discussed in Section III,

TABLE I
MAXIMUM READING DISTANCES OF THE NFC TAG IN DIFFERENT POSITIONS OF A TILE.

		Porcelain Tile		Ceramic Tile	
		Reader Orientation			
		Parallel (cm)	Normal (cm)	Parallel (cm)	Normal (cm)
NFC Tag positions	1	6.5	8.0	7.5	8.5
	2	6.5	8.0	8.0	8.5
	3	5.5	6.5	8.5	6.5
	4	4.5	5.5	5.0	5.0
	5	8.5	6.0	5.0	6.5
	6	5.5	7.0	5.0	7.0
	7	5.0	8.0	5.0	6.0
	8	6.5	6.0	6.5	5.5

with a transceiver connected to the MCU through an SPI interface.

An analysis of the maximum reading distance of the NFC board is needed to evaluate the effect of the tile on the reader-tag communication and, based on this, to design the tag-matrix under the floor. For this reason different positions of the NFC tag under the tile have been tested, for both normal and parallel orientation of the NFC-reader-antenna, in order to identify the maximum reading distances with the presence of either porcelain or ceramic tiles. The results reported in Table I show good performance in most of the cases for both the parallel and the normal orientation of the reader antenna. Since the optimal way to mount the NFC board on the shoe is applying it either on the side or on the back of the shoe itself the normal orientation has been preferred to the parallel one (see Figures 1 and 2).

III. IPv6-ENABLED WIRELESS SENSOR NETWORK ARCHITECTURE

As we move on to the era of the *Internet of Thing*s (*IoT*) [7], the capability of gathering, storing, and processing large amounts of data collected from tiny sensors in a centralized, efficient and low-cost way is becoming more and more critical. The paradigm of the IoT, backed by machine-to-machine (M2M) communication functionality, involves the combination of Internet-connected embedded devices with Web-based services, so that these devices are universally an integral part of the Internet [8].

So far, because of the complexity of the Internet communication standards and services, it has not been possible to natively use Internet capabilities on low-power devices with limited processing capabilities. ZigBee and a few other proprietary WPAN protocols have not been able to provide Internet integration, as they translate both address and commands between IP and Zigbee and thus IP stack gets terminated and since device discovery is performed in the *application* layer.

The major reason for opting for the *6lowPAN* protocol, acronym derived from *IPv6 over Low power Wireless Personal Area Networks*, is the native support of the IPv6 protocol stack on the end device. This has become reality by the encapsulation and header compression mechanisms defined by the 6lowPAN group that allow IPv6 packets to be sent to and received from over IEEE 802.15.4 based networks. In particular, the *network*, *transport* and *application* layers of the 6lowPAN protocol stack are the same as those of the IPv6 stack and the necessary changes exist in the *adaptation* layer on top of the IEEE 802.15.4 *medium access control* and *physical* layer.

As a result, our shoe-mounted sensor enjoys all the benefits that stem from IPv6, namely:

- easy connection to any existing, private or public, IP network infrastructure (eg. IEEE 802.11 WiFi networks) without translation gateways or proxies,
- mesh routing in the WPAN space with simultaneous support of the routability of packets between the IPv6 domain and the PAN domain,
- extensive scalability in terms of sensor node density,
- can be managed and diagnosed with a plethora of long-tested tools,
- can optionally support security inherently with compressed IPsec.

IV. CONCLUSION

In this paper, we propose a highly-reliable wearable, partially power-autonomous, wireless platform for health monitoring purposes. The design of the different component that comprise the sensor system has been described and supported by simulations and measurement results. Particular attention has been paid to the Adidas^{TM}antenna design, the innovation of which lies in the combination of both the aesthetic and the optimal performance aspects and the wearability.

REFERENCES

[1] C. Mariotti, G. Orecchini, M. Virili, F. Alimenti, and L. Roselli, "Rfid tag antenna embedded in concrete structures for construction industry," *Antennas and Propagation (EUCAP), 2012 6th European Conference on*, pp. 3469 –3472, march 2012.

[2] Y. Ge, K. Esselle, and T. Bird, "E-shaped patch antennas for high-speed wireless networks," *Antennas and Propagation, IEEE Transactions on*, vol. 52, no. 12, pp. 3213–3219, dec 2004.

[3] L. Peng, C.-L. Ruan, and X.-H. Wu, "Design and operation of dual/triple-band asymmetric m-shaped microstrip patch antennas," *Antennas and Wireless Propagation Letters, IEEE*, vol. 9, pp. 1069–1072, 2010.

[4] K.-H. Kim, J.-G. Song, D.-H. Kim, H.-S. Hu, and J.-H. Park, "Fork-shaped rfid tag antenna mountable on metallic surfaces," *Electronics Letters*, vol. 43, no. 25, pp. 1400 –1402, 6 2007.

[5] G. Orecchini, L. Yang, M. M. Tentzeris, and L. Roselli, "Wearable battery-free active paper-printed rfid tag with human-energy scavenger," in *Microwave Symposium Digest (MTT), 2011 IEEE MTT-S International*, june 2011, p. 1.

[6] J. Kymissis, C. Kendall, J. Paradiso, and N. Gershenfeld, "Parasitic power harvesting in shoes," *Wearable Computers, 1998. Digest of Papers. Second International Symposium on*, pp. 132–139, oct 1998.

[7] L. Atzori, A. Iera, and G. Morabito, "The internet of things: A survey," *Computer Networks*, vol. 54, no. 15, pp. 2787 – 2805, 2010.

[8] Z. Shelby and C. Bormann, *6LoWPAN: the wireless embedded internet*. Wiley, 2011, vol. 43.