Electro-textile slotted patch antenna for wearable passive UHF RFID tags

Electro-Textile Slotted Patch Antenna for Wearable Passive UHF RFID Tags

Aruhan Liu[1], Zhigang Wei[1], Xiaochen Chen[2], Leena Ukkonen[2], Johanna Virkki[2], Toni Björninen[2]

[1]Department of Electronic Engineering
City University of Hong Kong
83 Tat Chee Avenue, Kowloon, Hong Kong

[2]Department of Electronics and
Communications Engineering
Tampere University of Technology
Tampere, FI-33101, Finland

***Abstract* — We present the development and performance evaluation of wearable passive UHF RFID tags based on slotted patch antennas that are electromagnetically optimized for operation in the close proximity of the human body. The antennas comprise electro-textile conductor on a light-weight and conformal textile substrate. The required patch-to-ground interconnections are formed by means of sewing with conductive yarn and by wrapping the electro-textile over the edges of the substrate. Our results show that the slotted patch tags on 2 mm and 4 mm substrates achieve high read ranges of 3.2 and 8.2 m, respectively, when affixed to the upper back.**

***Index Terms* — Patch antenna, Slotted patch antenna, Electro-textile, Conductive yarn, Wearable antenna, RFID**

I. INTRODUCTION

The passive UHF (ultra-high frequency) RFID (radio frequency identification) technology based on battery-free ultra-low-power tags is a compelling approach for tracking people and for the development of wireless sensors in wireless body area networks that are an increasingly important area of research and offer a great potential for monitoring and communication in versatile application areas [1–3]. Further, the RFID enabled sensor tags are envisioned to provide remote monitoring of physiological parameters in assisted living and bedside applications in hospitals and nursery homes [4–5].

In body-centric systems, the fundamental challenge in antenna development raises from the proximity of the dissipative human body, which limits the attainable radiation efficiency of single-layer antennas [6]. In comparison, multi-layer structures, such as microstrip patch antenna, benefit from the antenna-body isolation provided by the ground plane. In this work, we show that in case of a slotted patch antenna, the conductor walls acting as the patch-to-ground interconnections are readily and reliably formed by sewing with conductive yarn. We also outline the process of the electromagnetic (EM) optimization of the antenna in the body-worn configuration and explore the size-performance trade-off related to the substrate thickness.

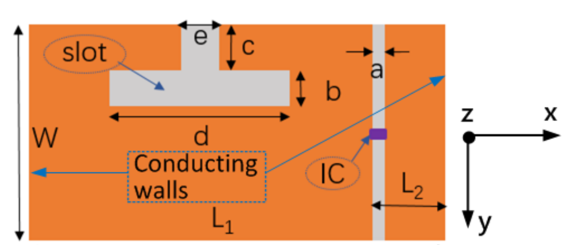

Fig. 1. Structural diagram of the studied slotted patch tag.

II. DEVELOPMENT OF THE WEARABLE SLOTTED PATCH TAG

The antenna development was initiated by considering the slotted patch antenna structure in Fig. 1. It originates from [7], where the structure was proposed to miniaturize a two-shorted patch antenna to achieve small metal mountable passive UHF RFID tags. Similar to metal mountable tags, wearable tags must also achieve platform tolerance in order to operate well near the human body composed of dissipative biological tissue.

In [7], the antenna was manufactured in a regular circuit board process, which is not a viable approach for wearable devices. To achieve an appropriate light-weight and conformal structure, which is compatible with textile manufacturing, in this work we implemented the antenna using nickel- and copper-plated Less EMF Shieldit Super Fabric (Cat. #A1220) as the electro-textile conductor and EPDM (Ethylene-Propylene-Diene-Monomer) cell rubber foam as the substrate. The electro-textile exhibits a sheet resistance of approximately 0.16 /sq and the dielectric constant and loss tangent of EPDM are 1.26 and 0.007, respectively, at 915 MHz. To gain insight on the influence of the substrate thickness on the performance of the antenna, we developed two antennas adapted for substrate thicknesses of two and four millimeters.

The electro-textile material comes with hot melt glue on the backside and is thus readily ironed on the substrate. To realize interconnections between the radiating patch and the ground plane, we studied the following approaches: wrapping the electro-textile over the shorted edges and sewing the two conductor layers together at either one of the shorted edges using conductive yarn (Shieldex multifilament silver plated thread 110f34 dtex 2-ply HC).

To account for the influence of the human body on the electromagnetic properties of the antenna, right beneath the substrate, we included a large rectangular block (thickness: 6 cm) of dielectric material with the dielectric properties of the human skin based on the frequency-dependent four-term Cole-Cole dispersion model with the parameters provided in [8]. The utilized model gives the dielectric constant and loss tangent of 41.33 and 0.414, respectively, for the skin at 915 MHz. By using this simplified body model, we were able to estimate the antenna impedance and radiation efficiency in the proximity of relatively large flat area of the body, such as the upper back. Optimization of the antenna structure was based on EM modelling in ANSYS HFSS with the target of maximal tag read range at 915 MHz.

Normally, the read range of passive tags is limited by the forward link operation, i.e., the efficiency of the wireless power transfer from the reader to the tag IC (integrated circuit). Assuming free-space conditions for site-independent comparison, the attainable tag read range at the spatial observation angles φ and θ of a spherical coordinate system centered at the tag is given by

$$d_{tag}(\phi,\theta)=\frac{\lambda}{4\pi}\sqrt{\left\{\frac{4\,\mathrm{Re}(Z_A)\mathrm{Re}(Z_{IC})}{|Z_A+Z_{IC}|^2}\right\}\frac{e_r D(\phi,\theta)EIRP}{P_{ic0}}}, \quad (1)$$

where λ is the wavelength of the carrier tone emitted by the reader, *EIRP* is the regulated equivalent isotropic radiated power, P_{ic0} is the wake-up power of the tag IC, e_r is the tag antenna radiation efficiency, D is the tag antenna directivity, and the factor in the curly brackets is the antenna-IC power transfer efficiency determined by the antenna and IC impedances Z_A and Z_{IC}, respectively [4]. In this work, we present all the read range results corresponding to $EIRP$ = 3.28 W (emission limit e.g. in European countries) in the direction of positive z-axis in Fig. 1. The RFID IC we used in this study was NXP UCODE G2iL RFID IC provided in fixture made of copper on a plastic film with 3×3 mm^2 contact pads. We attached the pads to the electro-textile using conductive epoxy (Circuit Works CW2400). The chip has the wake-up power of −18 dBm (15.8 µW) and we modelled it as a parallel connection of the resistance and capacitance of 2.85 kΩ and 0.91 pF, respectively.

The main target in the antenna optimization was good complex-conjugate impedance matching between the antenna and the IC, and as high as possible radiation efficiency in the body-worn configuration. We started the antenna development from the structure given in [7], but, as expected, due to the different operation environment, substrate thickness, and materials, modifications were needed to achieve maximal performance. Firstly, due to the lower permittivity of the substrate used in this work, we needed to increase the overall size of the antenna defined by parameters W and L slightly. Moreover, in comparison with [7], we found the optimum size of the slot defined by parameters b, c, e, and d, to be somewhat larger. The dimensions of the optimized antennas are given in Table I. The simulated read range versus frequency is presented along with the measured results in Section III.

TABLE I
DIMENSIONS OF THE ANTENNAS IN [mm]

L1	L2	W	a	b	c	d	e	t
63.7	10.1	29.8	2	5	7.68	27.1	5	2
64.4	13.6	33.5	2	5	4.75	31.1	5	4

III. RESULTS FROM SIMULATIONS AND WIRELESS TESTING

A. Wireless Testing Procedure

The tags were tested wirelessly using Voyantic Tagformance measurement system. It contains an RFID reader with an adjustable transmission frequency (0.8…1 GHz) and output power (up to 30 dBm) and provides the recording of the backscattered signal strength (down to −80 dBm) from the tag under test. During the test, we recorded the lowest continuous-wave transmission power (threshold power: P_{th}) at which a valid 16-bit random number from the tag was received as a response to the *query* command in ISO 18000-6C communication standard. In addition, the wireless channel from the reader antenna to the location of the tag under test was characterized using a system reference tag with known properties. As explained with details in [4], this enabled us to estimate the attainable read range of the tag.

B. Results and Discussion

The simulation results are presented in Fig. 2. In the body-worn configuration, the tags achieve the peak read ranges of 3.8 m and 6.7 m at the frequencies of 905 MHz and 920 MHz, which are close the targeted operation frequency of 915 MHz. Moreover, removal of the skin block does not result in significant shift in the frequency of the peak read range, but reduces the peak value. These observations correlate with the facts that the ground plane provides platform tolerance and the antennas were optimized for operation on body.

The measured read ranges of the tags in air are shown in

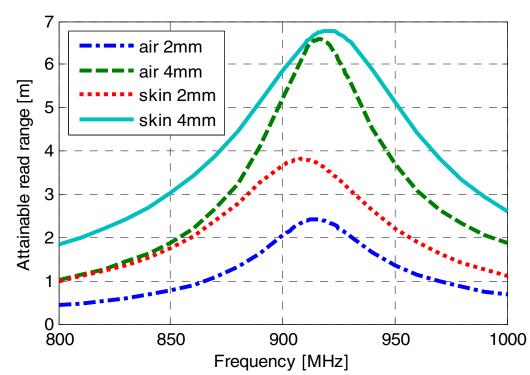

Fig. 2. Simulated attainable read range of the tags.

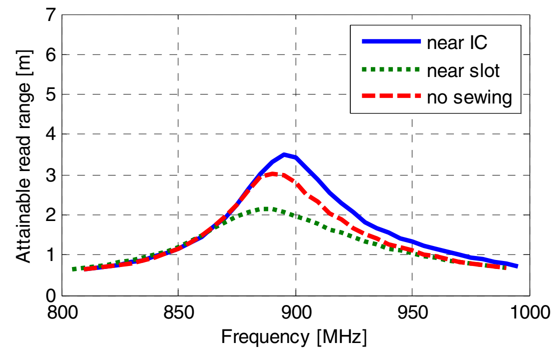

Fig. 3. Measured read range in air on 2 mm EPDM.

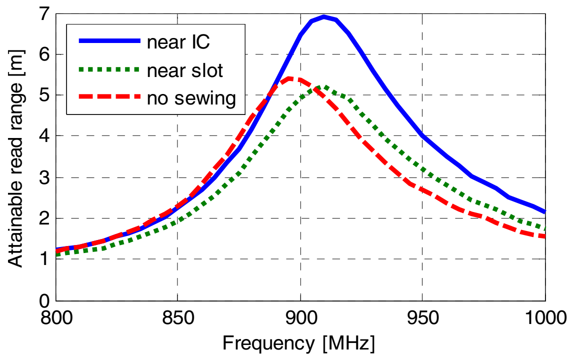

Fig 4. Measured read range in air on 4 mm EPDM.

Figs. 3 and 4. They present also the results with different approaches in implementation of the interconnection between the radiating patch and the ground plane. Here 'near IC' refers to sewn interconnection at the IC side of the tag with the electro-textile wrapped over the adjacent edge of the substrate, whereas in 'near slot' case the sewn and wrapped-over sides are interchanged. Finally, 'no sewing' refers to wrapping of the electro-textile over both sides of the substrate to establish the ground interconnections.

Firstly, it can be observed that doubling the substrate thickness from 2 mm to 4 mm greatly improves the tag's performance. However, substrate thickness of 4 mm may be bulky for wearable devices where unobtrusiveness is a top priority. Secondly, the sewn interconnection at the IC side of the antenna yielded the best performance. This corresponds with the observation that in the simulation the current density in the ground interconnection at this side of the antenna is notably lower than in the opposite side. This may have alleviated the negative impact of the limited conductivity of the yarn. The improvement over the approach of wrapping electro-textile over both edges may have been due to favorable impact of the sewing on the antenna impedance matching through parasitics, but further investigations are required to confirm this.

Finally, measurements were conducted to evaluate the tags' body-worn performance. Here the tag under test was affixed to the upper back of a male test subject. The results presented in Table II predict similar peak read range as the simulation results in Fig. 2. The read range above three meters achieved by the tag with the thickness of 2 mm enables many practical applications in the areas of identification and tracking of people using cloth-integrated RFID tags. Moreover, the high read range of 8.2 meters provided by the tag on 4 mm substrate demonstrates a compelling size-performance trade-off for applications demanding long detection ranges.

TABLE II

MEASURED ATTAINABLE READ RANGE ON BODY [m]

Substrate [mm]	2	4
Sewing near slot	3.20	4.80
Sewing near IC	3.25	8.20
Without sewing	3.25	4.75

VI. CONCLUSION

We presented two wearable passive UHF RFID tags based on slotted patch antennas on 2 mm and 4 mm thick textile substrates. Testing with the tags in air and worn on the upper back of a test subject showed that they are highly platform tolerant with similar performance in both cases. This is desirable in wearable applications where the distance between the body and clothing inevitably varies. We also showed that the conducting walls in the antenna structure can be readily and reliably formed by sewing the top and bottom layer electro-textiles together with conductive yarn. This simplifies the cloth-integration.

REFERENCES

[1] P. Van Daele, I. Moerman, P. Demeester, "Wireless body area networks: status and opportunities," in *Proc. 2014 URSI General Assembly and Scientific Symposium*, Beijing, China, 4 pages.

[2] Ya-Li Zheng, Xiao-Rong Ding, Yuan-Ting Zhang, et al., "Unobtrusive sensing and wearable devices for health informatics," *IEEE Trans. Biomed. Eng.*, vol. 61, no. 5, pp. 1538–1554, May 2014.

[3] S. Movassaghi, M. Abolhasan, J. Lipman, D. Smith, A. Jamalipour, "Wireless body area networks: a survey," *IEEE Commun. Surveys Tuts.*, vol. 16, no. 3, pp. 1658–1686, Third Quarter 2014.

[4] F. Long, X. Zhang, T. Björninen, J. Virkki, L. Sydänheimo, Yan-Cheong Chan, L. Ukkonen, "Implementation and wireless readout of passive UHF RFID strain sensor tags based on electro-textile antennas," in *Proc. 2015 European Conf. Antennas Propag.*, Lisbon, Portugal, 5 pages.

[5] S. Amendola, G. Bovesecchi, P. Coppa, G. Marrocco, "Thermal characterization of epidermal RFID sensor for skin temperature measurements," in *Proc. 2016 IEEE AP-S Intl. Symp. Antennas Propag.*, Fajardo, Puerto Rico, USA, pp. 461–462.

[6] R. M. Mäkinen, T. Kellomäki," Body effects on thin single-layer slot, self-complementary, and wire antennas," *IEEE Trans. Antennas Propag.*, vol. 62, no. 1, pp. 385–392, Jan. 2014.

[7] T. Björninen, F. Yang, "Signal strength readout and miniaturised antenna for metal-mountable UHF RFID threshold temperature sensor tag," *IET Electronics Lett.*, vol. 52, no. 22, pp. 1734–1736, Oct. 2015.

[8] S. Gabriel, R. W. Lau and C. Gabriel, "The dielectric properties of biological tissues: III. parametric models for the dielectric spectrum of tissues," *Phys. Med. Biol.*, vol. 41, no. 11, pp. 2271–2293, Nov. 1996.