Wearable E-Textile Split Ring Passive UHF RFID Tag: Body-Worn Performance Evaluation

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***Abstract*—We present a wearable e-textile passive UHF RFID tag based on a split ring resonator antenna. The antenna was optimised using a full-wave electromagnetic solver and the prototyped tag was tested in wireless measurements. The detection range of the tag is 2.8 metres at 915 MHz when affixed to the upper back of a person on a textile substrate with the thickness of only two millimetres. In the wireless measurement, we found a close match with the simulations where a homogenous dielectric cuboid representing the torso of a person and studied the impact of non-optimal antenna-body alignments and separations. Overall, the results indicate that the uniplanar split ring antenna achieves robust operation required in the practical wearable applications.**

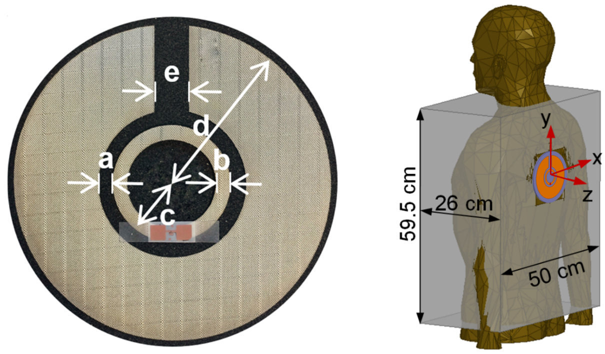
Keywords—Split ring antenna, electro-textile, Wearable antenna, RFID

I. Introduction

Wireless body area networks (WBAN) are bringing a new era for the wireless medicine and healthcare by enabling the monitoring of physiological parameters continuously and non-intrusively in home care without restricting the patients' mobility [1][2].

In this conception, wireless sensors are among the most essential components. They will sample multiple physiological parameters from different locations on and inside the body, harvest and relay energy among the sensor nodes, and convey the data wireless to off-body systems. To achieve energy autonomous systems, wireless sensing using passive ultra-high-frequency (UHF) radio-frequency identification (RFID) technology has been proposed as an attractive solution. By taking the advantage of the battery-free working principle of passive UHF RFID tags combined with novel antenna-sensor implementations, the sampled data can be retrieved through the backscatter radio link. Without the necessity of the battery and active radio transmitter, the sensor can be small, lightweight and easily embedded into clothing or affixed to the skin.

From the perspective of radio wave propagation, human body is a complex and heterogeneous medium composed of various highly dissipative biological tissue. When working in the proximity of this lossy medium, the radiation performance of antennas is limited and impaired. In face of this challenge, numerous topologies for wearable antennas has been studied [3][4]. In our previous study [5], we found split ring resonator antenna an attractive choice for wearable passive UHF RFID tags, due to its simple, uniplanar, and conformal structure as well as its inductive impedance facilitating the impedance matching with RFIC IC. In this work, we present reduction in size of the antenna and evaluate the performance of a new e-textile prototype in wireless measurements. In addition, we also investigate how the alignment of the antenna with respect to the body affects the performance of the tag.



Geometrical parameter (mm)	a	b	c	d	e
	3.0	2.8	11.1	30.2	6.6

Fig. 1. Prototyped SRR antenna and the cuboid model (the anatomical body model of an adult male is shown only for dimension comparison).

II. Antenna Development

The studied wearable tag is based on a split ring antenna, which consists of two concentric conductor rings with the split gaps on the opposite sides. Fig. 1 shows a fabricated tag with its geometrical parameters. We patterned the two rings from Less EMF Shieldit Super Fabric with a laser cutter and used 2 mm thick EPDM (Ethylene-Propylene-Diene Monomer) as the substrate. The sheet resistance of the conductive fabric is 0.16 Ω/Sq. and the dielectric constant and loss tangent of EPDM are 1.26 and 0.007, respectively, at 915 MHz. The conductive fabric comes with a layer of hot-melt glue in its backside and thus we adhered the fabric to the substrate by ironing and the NXP UCODE G2iL series RFID IC (wake-up power: 15.8 µW) to the inner ring split using Circuit Works CW2400 conductive epoxy.

In the electromagnetic modelling, we used ANSYS High Frequency Structure Simulator (HFSS). Here we used an equivalent parallel connection of capacitance and resistance of

0.91 pF and 2.85 kΩ, respectively, to model the RFID IC [6]. In order to account for the effect of the human body on the antenna's electromagnetic parameters, we included a cuboid (26 mm × 59.5 mm × 50 mm) in the simulation model and assigned the dielectric properties of skin on it. The relative permittivity and loss tangent of skin were 41.33 and 0.414, respectively at 915 MHz, according to the frequency dependent four-term Cole-Cole relaxation model [7]. We chose the size of the dielectric block to simulate the upper trunk of human body. From the modelling, we obtained the antenna impedance, radiation efficiency, and directivity. Using these data, we were also able to predict the attainable read range (d_{tag}) of the tag. It is the most important performance indicator. Due to the high sensitivity of the RFID reader's receiver, the detection range of the tag is mostly limited by the distance at which the tag IC can be remotely powered up. By applying the Friis' free-space propagation formula, we can estimate d_{tag} as

$$d_{tag} = \frac{\lambda}{4\pi}\sqrt{\frac{De_r\tau EIRP}{P_{ic0}}}, \qquad (1)$$

where D is the antenna directivity, e_r is the radiation efficiency, P_{ic0} is the RFID IC wake-up power threshold, $EIRP$=3.28 W (emission limit in European countries) and τ is the power transfer efficiency given by

$$\tau = \frac{4\mathrm{Re}(Z_A)\mathrm{Re}(Z_c)}{|Z_A+Z_C|^2}. \qquad (2)$$

In equation (2), Z_A is the antenna impedance and Z_C is the impedance of RFID IC. Power transfer efficiency measures how efficiently the tag antenna transfers the energy it receives from the reader to the tag IC. It reaches its maximum value when the antenna is complex-conjugate matched with the IC. According to (1), d_{tag} is in positive correlation with antenna gain (the product $D{\cdot}e_r$) and the power transfer efficiency. Thus, in the optimisation of the geometrical dimensions of the antenna, we targeted at both good complex-conjugate impedance matching with the IC and a high antenna gain. According to the simulation results, the proposed antenna archives a very high power transfer efficiency 95% at 915 MHz. The directivity and radiation efficiency are 7.33 dBi and 1%, respectively. Here both, the high directivity and low radiation efficiency are explained by the electromagnetic interactions between the antenna and the human body. The simulated d_{tag} peaks at 2.75 metres at 915 MHz as shown in the Fig. 2.

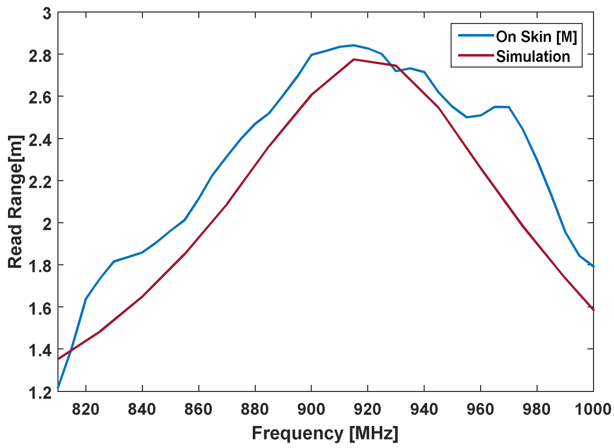


Fig. 2. Comparison of the read range between the simulation and on-skin measurement of the tag with 2 mm EPDM

III. Results From Wireless Testing

The prototyped tag was 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}). Here we defined P_{th} as the lowest power at which a valid 16-bit random number from the tag is 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 characterised using a system reference tag with known properties. As explained with details in [8], this enabled us to estimate the attainable read range of the tag (d_{tag}) versus frequency from

$$d_{tag} = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{\Lambda}\frac{P_{th*}}{P_{th}}}, \qquad (3)$$

where P_{th} is the measured threshold power of the tag, Λ is a known constant describing the sensitivity of the system reference tag, P_{th*} is the measured threshold power of the system reference tag and $EIRP$ is the emission limit of an RFID reader given as equivalent isotropic radiated power. Based on the calibration data provided by the manufacturer of the measurement system, we have estimated that the combined static uncertainty in d_{tag} due to variability in the system reference tag (Λ) and the output power meter of the reader (P_{th}, P_{th*}) is less than 5% throughout the studied frequency range.

In the wireless measurement, we found that frequency of peak d_{tag} shifts to around 960 MHz when placed on top of the

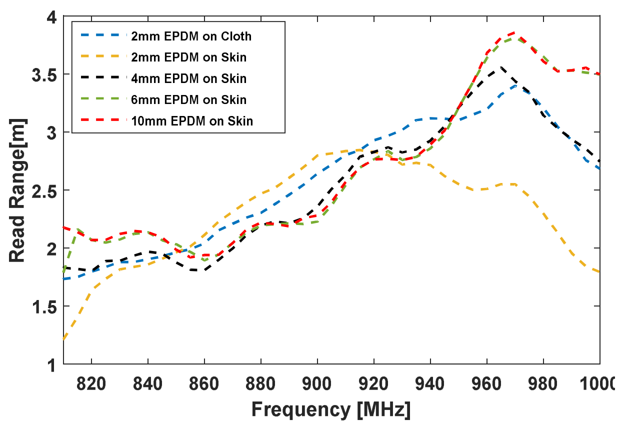


Fig. 3. Comparison of the measured tag read range with different substrate thickness

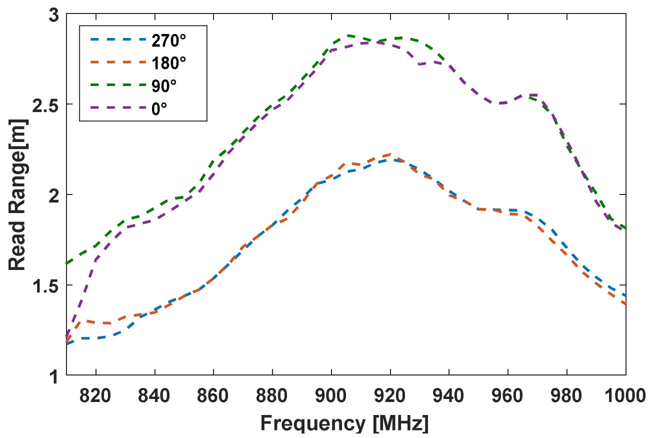


Fig. 4. Measured read range with different rotation of the tag with 2 mm EPDM

subject's pure cotton T-shirt (thickness: 1 mm) which increases the distance between the tag and human body. In order to investigate the impact of cloth thickness further, tags on 4 mm, 6 mm and 10 mm EPDM substrate were also fabricated and tested on-body. The results in Fig. 3 show that the split ring tag is robust against variable antenna-body separation: despite its uniplanar structure, it maintains d_{tag} above 2.6 metres (i.e. within 15 cm from the optimised scenario) at the different distances tested.

We also tested how the rotation of the antenna from 0° to 360° around the z-axis in Fig. 1 impacts d_{tag}. Here, we rotated the tag with a step of 90° when affixed to the upper back of a test subject. Due to the linear polarization of the tag antenna in the plane perpendicular to the split gap in the outer ring, the linearly polarised read antenna was also rotated accordingly to avoid polarization mismatch. Fig. 4 shows the measured read range of the four rotations. A drop of 0.7 m in d_{tag} was observed when the tag had the 270° or 180° rotation. The reason behind this may be the asymmetry between the breadth and height of the human body. The rotation test characteristics the human body effects in antenna performance and provides insight for the practical body-worn implementations.

IV. Conclusion

We presented the body-worn modelling and testing of a passive UHF RFID tag based on a split ring antenna made of conductive textile. As compared with our previous work, we implemented the antenna from e-textile and reduced its footprint size by 25% while maintaining similar performance with an attainable tag read range of 2.8 metres at 915 MHz. We also tested the tag with four different substrate thickness and proved that the uniplanar split ring antenna provides the robustness toward antenna-body separation that is required in practical wearable applications where the cloth thickness and fitting varies.

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