A Broadband UHF Tag Antenna for Near-Field and Far-Field RFID Communications

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Abstract. *The paper deals with the design of passive broadband tag antenna for Ultra-High Frequency (UHF) band. The antenna is intended for both near and far fields Radio Frequency Identification (RFID) applications. The meander dipole tag antenna geometry modification is designed for frequency bandwidth increasing. The measured bandwidth of the proposed broadband tag antenna is more than 140 MHz (820–960 MHz), which can cover the entire UHF RFID band. A comparison between chip impedance of datasheet and the measured chip impedance has been used in our simulations. The proposed progressive meandered antenna structure, with an overall size of 77 × 14 × 0.787 mm^3, produces strong and uniform magnetic field distribution in the near-field zone. The antenna impedance is matched to common UHF chips in market simply by tuning its capacitive and inductive values since a perfect matching is required in the antenna design in order to enhance the near and the far field communications. Measurements confirm that the designed antenna exhibits good performance of Tag identification for both near-field and far-field UHF RFID applications.*

Keywords

Chip, tag antenna, far-field, near-field, Ultra-High Frequency (UHF), RF identification (RFID).

1. Introduction

Radio Frequency Identification (RFID) is a system based on non-contact bidirectional identification technology. It aims to storing and extracting information using RFID tags [1]. These tags use backscatters modulation to communicate with the readers. The reader emits electromagnetic waves that are captured by the tag antenna in order to feed the chip, which enables it to respond to the reader by changing its input impedance between two states Z_c^1 and Z_c^2 [2]. This change in impedance state modulates the signal backscattered by the tag and uses it to respond to the reader.

It appears today that one of the limitations of RFID systems is that they do not operate at short distances (near field). This can be urgently analyzed to invent antennas for UHF near-field RFID applications. To overcome this problem, some work has been reported to address the design of reader and tag antennas for near-field RFID applications. Several papers have been published on near-field reader antennas. In [3], the author proposed a novel RFID reader antenna for simultaneous near-field and far-field operations at UHF band. In [4], a broadband segmented loop antenna was proposed for UHF near-field RFID applications. In [5], the proposed compact near-field reader antenna was based on split-ring-resonator (SRR) structure and miniaturized to a special small size for mobile RFID application. In [6], the author proposed a dual-loop near-field antenna for UHF RFID readers.

However, there are only a few papers about the performance of RFID tag antennas, especially in the aspects of compact size and broadband UHF near-field RFID applications, for example, the design of a near-field reader and tag antennas in UHF that can be used for various smart shelves [7]. In [8], two compact near field UHF tag antennas with a Split Ring Resonator (SRR) structure were proposed for UHF near-field RFID applications, but these antennas have narrow bandwidth (13 MHz).

In this paper, we propose a broadband tag antenna for near-field and far-field RFID applications. The effects on RFID tag antenna parameters due to chip impedance variation between impedance from datasheet and measured impedance will be addressed.

In practice, frequently the performance of tag antennas for near-field RFID applications could be significantly degraded due to the complex physical environments. With the aid of computational electromagnetic (CEM) tools, RFID tag communication in the near and far field can be analyzed and optimized to improve the performance of RFID systems. We selected ANSOFT's High Frequency Structure Simulator (HFSS) as the computational electromagnetic (CEM) modeling tool for RFID tag antenna design [9].

The proposed antenna achieves good impedance matching and uniform magnetic field distribution in the region near the antenna. Design details, simulated results, and a fabricated prototype are presented below.

2. UHF Near-Field RFID Antenna

We can divide UHF RFID into two categories based on the mechanism of communication between the reader antenna and the tag antenna. These mechanisms are far-field and near-field UHF RFID. Far-field UHF RFID uses electromagnetic waves, meanwhile near-field UHF RFID is based solely on a magnetic field. In most of the near field RFID systems, the interaction between the reader antenna and tag antenna is based on inductive coupling because the reactive energy is stored in the magnetic field [1]. In order to successfully design a near-field UHF RFID system, it is important to investigate the antenna coupling between reader and tag. If the tag antenna is small, the magnetic field generated by the reader antenna is hardly perturbed by the tag antenna, and the coupling coefficient is proportional to [10]:

$$C \propto f^2 N_{Tag}^2 S_{Tag}^2 B^2 \alpha \qquad (1)$$

where f is the frequency, N_{Tag} is the number of turns of the coil tag antenna, S_{Tag} is the cross-section area of the coil, B is magnetic field density at the tag location created by the reader antenna, and α is the antenna misalignment loss.

Formula (1) indicates that the coupling in a near-field RFID system with a coil is dependent on the magnetic field density generated by the RFID reader antenna. Also, the coupling between the tag and the reader depends of turns of the coil tag antenna. The design of the RFID tag antenna has a great influence on conservation or improvement of the magnetic field. The magnetic field is related to the number of turns, diameter, shape and length of the antenna tag. A tag antenna with a strong magnetic field allows improve the magnetic coupling and the reliability of near-field communication and is therefore desired in UHF near-field RFID systems.

3. Design of the Proposed Antenna

The antenna impedance Z_a is $R_a + jX_a$ and the chip impedance Z_c is $R_c + jX_c$ .The chip impedance is a nonlinear load whose complex impedance Z_c (f, P) varies with the frequency f and the input power P applied to the chip. The change of the chip impedance state causes the undesired impedance mismatch between the tag antenna and the chip. The varying impedance mismatch results in the variation of the reflected signals.

The size of the RFID tag is important for many RFID applications because a small RFID tag requires less area on the product. The ideal RFID tag antenna length is of the order of the wavelength of the frequency at which the antenna is designed to operate. The most important thing in the design of an RFID is to reduce the size of the antenna. At this point, a linear wire antenna whose structure is simple is most commonly used for a tag antenna, such as a dipole antenna and a folded dipole antenna. In [11], a wideband dipole-type RFID tag is miniaturized by utilizing a meander line structure to reduce the tag size without significantly degrading its performance.

3.1 RFID Chip Model from Datasheet

Impedance matching between the antenna and the chip is an essential part of the antenna design. It directly influences RFID system performance characteristics such as the read range of the tag. For the design of RFID antennas, one must know first of all the impedance value which is presented to the input of the antenna. The input impedance of the antenna should be the impedance matched of the chip to obtain maximum transfer of energy to power the RFID chip. The chip impedance values are usually taken by tag designers from IC manufacturers' datasheets, which specify the impedance at the threshold power level, but just for one or two frequencies and often only for a bare die [12]. Moreover, the value of the chip impedance still varies with the frequency and the input power. In the design phase of RFID tag antenna using HFSS software, it is necessary to use the measured impedance of the chip to obtain a better impedance matching.

Firstly the proposed antenna structure is optimized for a tag chip with datasheet impedance $Z_c^{datasheet} = (30.4 - j208)\,\Omega$ at a resonant frequency of 868 MHz. The load antenna impedance should be $Z_a = (30.4 + j208)\,\Omega$ for matching the maximum power between the antenna and the chip.

The proposed antenna structure is shown in Fig. 1. The antenna is composed of a small rectangular feeding loop and a progressively meandered dipole antenna radiating body, which are T-match [13]. The antenna parameters are as follows: **L_1 = 24.6 mm**, L_2 = 21 mm, **L_3 = 16 mm**, L_4 = 73 mm, L_5 = 1 mm, L_6 = 2 mm, L_7 = 2.5 mm, L_8 = 2.5 mm, L_9 =3 mm, L_{10} = 3.5 mm, L_{11} = 2 mm, L_{12} = 0.5 mm, W_1 = 9.5 mm, W_2 = 7.5 mm, W_3 = 6 mm, W_4 = 6.5 mm, W_5 = 7 mm, W_6 = 7.5 mm, W_7 = 1 mm, W_8 = 0.5 mm, W_9 = 0.5 mm. The antenna is simulated on a Rogers RT/duroid® 5880 substrate (thickness H = 0.787 mm, relative dielectric constant ε_r = 2.2, and loss tangent tan δ = 0.009) with an overall size of 77 × 14 mm^2.

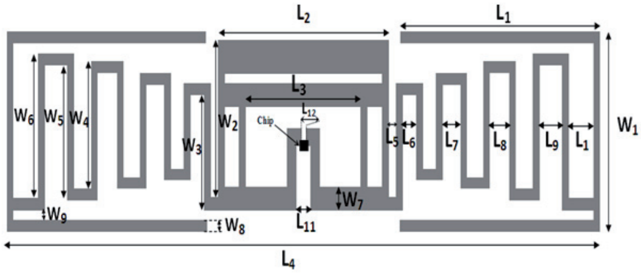

Fig. 1. Geometry of the proposed meandered antenna.

The RFID tag IC selected for this design is an Alien Higgs-3 RFID IC [14]. The parallel resistance and capacitance of the Higgs-3 chip are 1500 Ω and 0.85 pF, respectively. The RFID chip is soldered directly on the antenna through the two connection pads of the chip.

The return loss of the proposed antenna is plotted versus frequency in Fig. 2 as simulated using both chip impedance value from IC manufacturers' datasheets and the

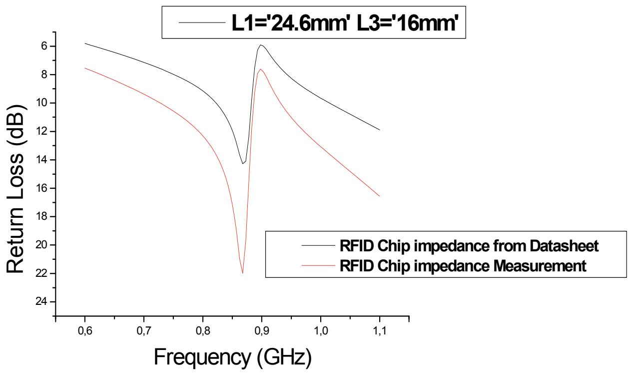

Fig. 2. Simulated return loss for the proposed broadband tag antenna.

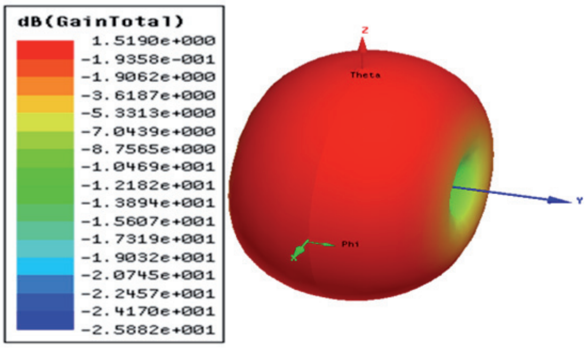

Fig. 3. 3-D far-field radiation plot at 867.7 MHz.

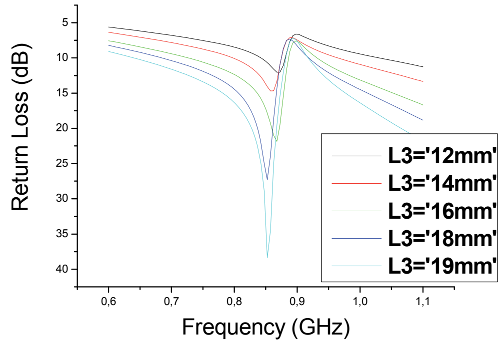

Fig. 4. Return loss of the tag antenna for various L_3.

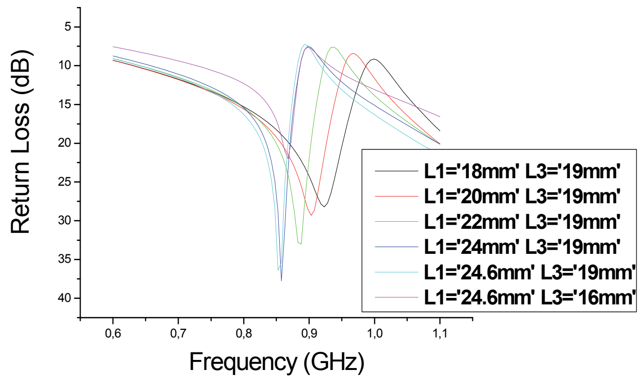

Fig. 5. Return loss of the antenna for various L_1.

chip impedance measurement. The return loss of 14.27 dB is obtained at the frequency of 867.7 MHz with RFID chip impedance from the datasheet. Good impedance matching was achieved at 867.7 MHz for a 21.98 dB return loss with the chip impedance measurement. The 3-D radiation plot of the antenna is shown in Fig. 3.

3.2 RFID Chip Impedance Measurement for UHF Tag Design

The impedance of the chip was varied according to the frequency and the received power by the chip. The measured impedance was carried through two configurations: on one hand, fixed frequency and power sweep $Z_c^i(f_1, p)$, and on the other hand, fixed power and frequency sweep $Z_c^i(f, p_1)$. A Short-Open-Load calibration procedure is then used to extract chip impedance values [15]. The measured impedance value of the chip is $Z_c^{Measurement} = (26 - j163)\,\Omega$ [16].

A small rectangular loop is adjusted for a better transmission of a power between the tag antenna and the chip. The return loss of RFID tag antenna is shown in Fig. 4 with variation of the parameter L_3. It can be seen in Fig. 4 which illustrates the impedance conjugate-matching that it is optimized while L_3 is 19 mm. The return loss of 38.3 dB is obtained at the frequency of 852.5 MHz.

According to the results, the decrease in the size of the loop can decrease the impedance of the antenna in both real and imaginary parts. The resistance and reactance of the antenna input impedance are strongly related to the change of the chip's measurement impedance.

This tag antenna can be tuned by trimming to provide a good match for the chip impedance. Length of L_1 can be modified to obtain optimum resistance and reactance matching which should be similar to the chip impedance [17]. Return loss of the tag antenna is strongly influenced by trimming as it is shown in Fig. 5.

Hence, it can be seen that the good impedance can be achieved ($26.09 + j158.7\,\Omega$ at 857.6 MHz) with $L_1 = 24$ mm and $L_3 = 19$ mm. The return loss of -21.9 dB obtained at the frequency of 867.7 MHz is shown in Fig. 5. We chose Europe RFID Band (865–868 MHz) with $L_1 = 24.6$ mm and $L_3 = 16$ mm.

A broadband tag antenna with a desired performance over the entire UHF RFID bandwidth of 860–960 MHz would be advantageous for the RFID system to surmount the operating frequency change and impedance variations due to the fabrication process errors and effects of problematic surfaces (metals, liquids, and human body) on tag antenna. The simulated bandwidth ($RL \geq 3$ dB) can be more than 200 MHz (800–1000 MHz) for UHF band and the simulated operating bandwidth ($RL \geq 10$ dB) can reach about 155 MHz (730–885 MHz) or 17.8 % centered at 868 MHz. The fabricated tag antenna should be matched to the measured impedance $Z_c^{Measurement} = (26 - j163)\,\Omega$ in order to obtain the best performances.

4. Field Analysis of Tag Antenna

The technology of near-field UHF RFID has become the target of interest due to the great potentials in RFID applications. The magnetic field intensity generated by RFID tag antenna should be increased to improve the communication in near-zone applications. The most common UHF tag antennas for Far-Field Communication (FFC) may not perform well in Near-Field Communication (NFC).

The current on the side of the feed loop is not same magnitude as that on the side of the radiating body but it is reduced progressively [18]. According to Ampere's theorem, the strength of the magnetic field decreases with the diminution of the current. The reduction of the magnetic field produces a distribution of this field which is not uniform for near-field RFID applications. The tag structure can produce large currents along the antenna so that a strong magnetic field distribution is excited in the adjacent region around the tag antenna. Simulations of the surface current distribution of the antenna at 867 MHz is shown in Fig. 6. It is clear that the current is intensive on the meander line of the proposed antenna.

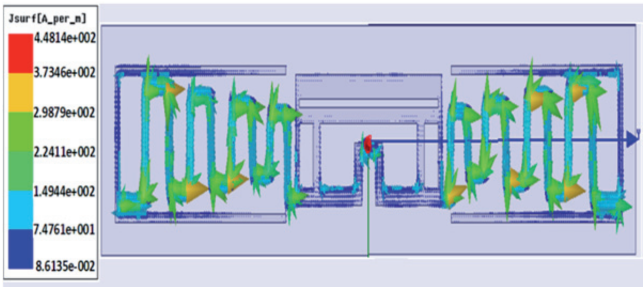

Fig. 6. Surface current distribution at 867 MHz.

5. Measurements Setup

The experimental setup in an anechoic chamber is illustrated in Fig. 7. We characterized the performances of the tag in the near field and the far field. A mono-static system uses the same reader antenna for both transmitting and receiving [10]. We propose a "Transmitter-Tag-Receiver" link in order to determine the maximum distance that allows the activation of the tag. The tag was placed at different distances from the reader antenna, moving in both near- and far-field regions, and oriented in the direction of maximum gain. We used Agilent E4438C ESG vector signal generator (50 kHz–6 GHz) as a transmitter. The reader with the variable power output sends a signal to activate the tag and decode the data encoded in the chip. This enabled us to determine the minimum reader output power required for activating the tag as a function of frequency. The tag response is received on HP Agilent 54855A Infiniium oscilloscope.

For accurate measurements we use a standard horn antenna which is linearly polarized, with 6 dB gain in 800-1000 MHz band. We use a circulator in order to isolate

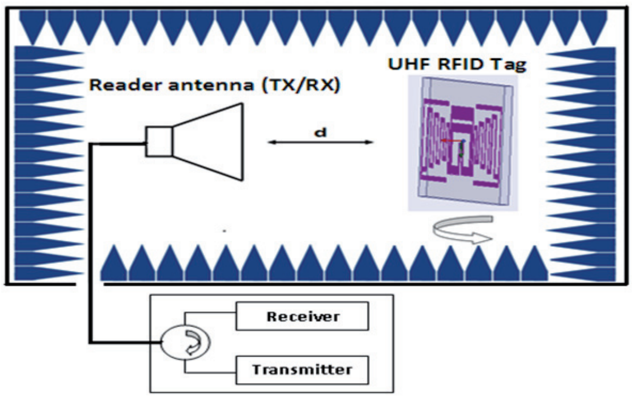

Fig. 7. Experimental setup of the tag in the mono-static configuration.

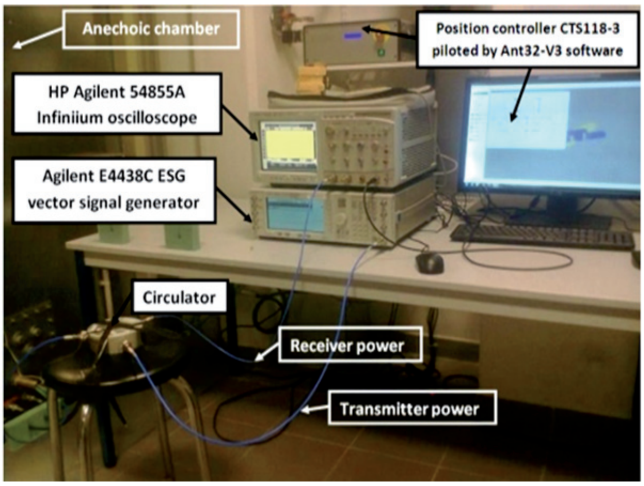

Fig. 8. Photograph of the measurement equipment.

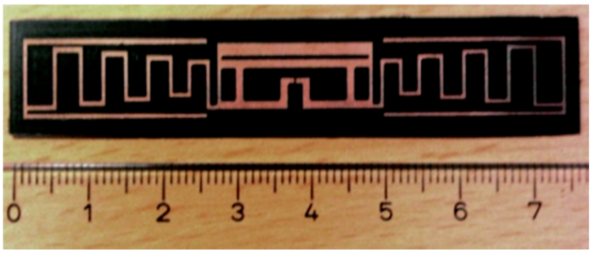

Fig. 9. UHF RFID tag used in measurements.

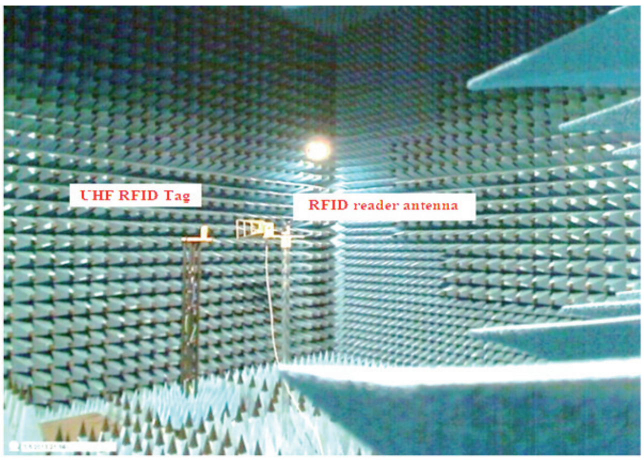

Fig. 10. UHF RFID tag range measurement using anechoic chamber.

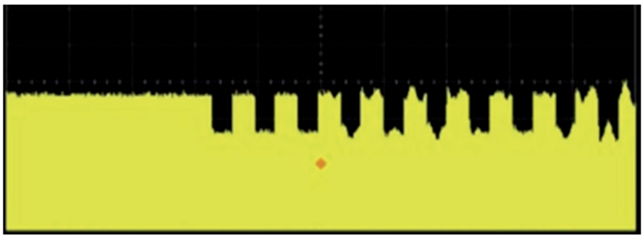

Fig. 11. Portion of the received tag response at 867 MHz.

the transmission and the reception channels. All measurements were done with a mobile holder for the receiving UHF tag antenna which was able to rotate on 360 degrees.

The photograph of the measurement equipment is shown in Fig. 8. A prototype of the antenna was fabricated, as shown in Fig. 9. The photograph of the experimental setup to measure reading range in the anechoic chamber is shown in Fig. 10. The received tag response was clearly visible at 867 MHz as shown in Fig. 11.

The typical UHF near-field RFID tag (Impinj UHF button type tag) works with pure near-field characteristic and was used for short distance reading (3.7 cm) [19]. Furthermore, for near-field communication, many applications need longer read ranges. Our antenna is designed to operate well in the far field, and demonstrates also good performances with inductive coupling for near-field RFID applications. Fig. 12 shows the minimum power necessary for tag to respond versus frequency in various distances (near-field/far-field) between the tag and the reader.

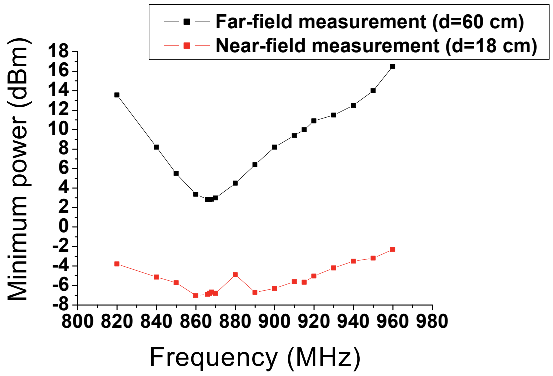

Fig. 12. Minimum power vs. frequency for near-field and far-field reading measurements.

For near-field and far-field reading measurements, our antenna structure has a wide bandwidth (820-960 MHz) for UHF band that covers all frequency bands stated for UHF RFID devices. The minimum power needed for generating a correct response to a command at 867 MHz for distances $d = 60$ cm (far-field) is approximately 2.84 dBm. The center frequency varies only ±1 MHz around the operating frequency of 868 MHz.

We can calculate the read range of the tag using Friis free-space formula as follows [2]

$$d = \frac{\lambda}{4\pi}\sqrt{\frac{P_t G_r G_T \tau}{P_{th}}} \tag{2}$$

where d is the distance between the reference antenna (reader) and the tag, P_t is the power of the signal transmitted by the reader, G_r is the gain of the reader, G_T is the gain of the tag, P_{th} is the power threshold value necessary to the activation of the tag chip, λ is the free space wavelength and τ is the power transmission coefficient given by [2]:

$$\tau = 1 - \left|\Gamma^*\right|^2 = \frac{4R_a R_c}{\left|Z_a + Z_c\right|^2} \tag{3}$$

where $0 \le \tau \le 1$ and Γ^* is the reflection coefficient which defines the mismatch between the chip and antenna impedance

$$\Gamma^* = \frac{Z_c - Z_a^*}{Z_c + Z_a}\ . \tag{4}$$

We deduce the maximum reading range of the tag when the power transmitter by the reader is maximum using the following equation [2], [10]

$$d_{\max} = d.\sqrt{\frac{P_{EIRP}}{G_r P_{EIRP_{\min}}}} \tag{5}$$

where P_{EIRP} is the power of the signal transmitted by the reader (i.e. $P_{EIRP} = 3.28$ watts in Europe and 4 watts in North America) and $P_{EIRPmin}$ is the minimum output power required to the activation of the chip.

Different regions of the UHF tag antenna have different read ranges in accord with the field intensities. For near-field reading measurement, less minimum power is required to activate the tag because the field intensity is stronger and uniform compared to the far-field region.

The minimum power required to read the tag in the near-zone at 868 MHz is approximately of -6.68 dBm. Measurements show that the reader antenna has a readable range of 18 cm for parallel orientation of our proposed tag along the positive Z-axis.

For far-field operation, gain, sensitivity of the tag, and orientation of tag and reader antennas determine the read range.

The orientation of a RFID tag with respect to the reader is an important factor that impacts reading performance of an RFID system. An RFID tag is placed at a fixed distance (60 cm) from the reader antenna. Depending on the angle θ, we may need to change the alignment. We vary the direction of our tag depending on the angle θ and thus determine the minimum received power for the activation with different orientation of our tag. Fig. 13 shows minimum power versus angle at 868 MHz (calculated from minimum power measured at $d = 60$ cm).

In the far-field of the reader antenna, the minimum reader output power needed for tag to respond is approximately of 2.5 dBm at 868 MHz when the angle $\theta = 70°$. If the tag antenna is directly facing the reader antenna $\theta = 0°$, the power required to activate our tag is approximately of 2.86 dBm. The maximum reader output power needed for tag to respond is approximately of 3.86 dBm at 868 MHz

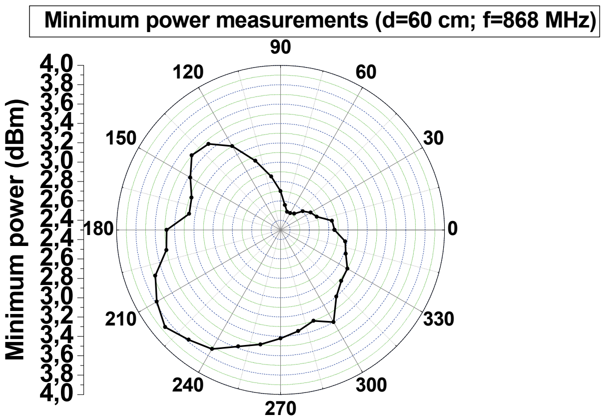

Fig. 13. Minimum power measurements vs. angle.

when the angle $\theta = 220°$. The orientation of this tag relative to the reader's antenna affects the amount of power that a tag receives, and hence the read range is affected as well. The exact positions and orientations of the RFID tag and the reader antenna should be determined to ensure that the tag will be in the reading zone of the reader.

To further verify the performance of the proposed UHF tag antenna for simultaneous near-field and far-field operations, the ThingMagic M6e embedded RFID reader module [20] was used with a standard horn antenna in the free space to detect our prototype antenna tag. This RFID teader module supports the ability to transmit up to +31.5 dBm for the UHF RFID band of Europe (865.6–867.6 MHz).

The read range measurement of the tag was performed inside a building corridor. Its dimensions are 19 m × 2.5 m × 3 m and it has three entries. The test setup for testing the proposed tag is illustrated in Fig. 14. Figure 15 shows minimum power versus distance in RFID system.

For a 25.5 dBm transmit power with linear polarization, the maximum reading range measured of the tag antenna achieves 12.5 m for the UHF RFID band of Europe and the measured receiver sensitivity is -60 dBm. The near-field range is approximately of 40 cm under the transmission power level of 4 dBm and the receive signal strength (RSS) of the tag response is –41 dBm.

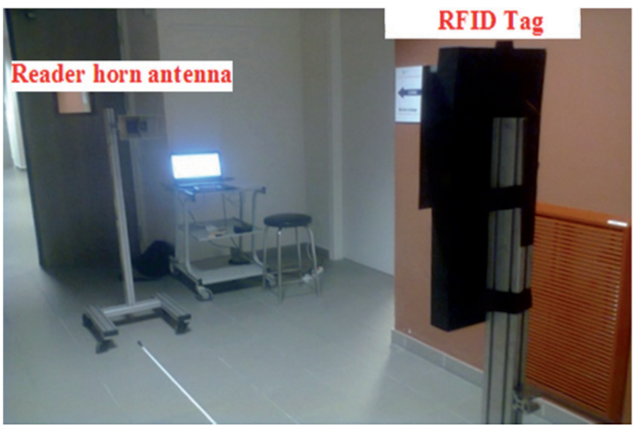

Fig. 14. Experimental setup for testing the proposed UHF RFID tag.

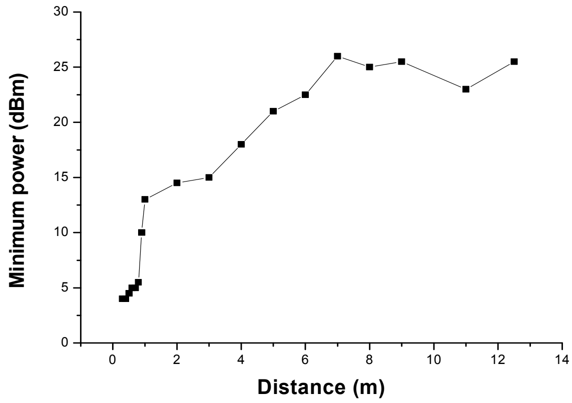

Fig. 15. Minimum power vs. distance in RFID system.

6. Conclusion

A novel broadband antenna for passive UHF RFID tag applications is presented. The impedance of the tag antenna can be simply adjusted by changing the lengths L_1 and L_3. The meander dipole tag antenna geometry has been proposed for UHF frequency bandwidth increasing (820-960 MHz). The power sensitivity of the tag was also measured by sweeping the power source and determining the minimum power level required to read the tag. Such a tag antenna design is found to be very promising for near-field and far-field UHF RFID applications.

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