Antennas for Small Metal Mountable Passive UHF RFID Tags: Challenges and Advances

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***Abstract*—We review the performance analysis of RFID tags and the special features in metal mountable tags. The impact of the reader antenna polarization on the attainable read range of the tag is analyzed and included in the conventional link analysis. A new metrics for the reliability of the reader-to-tag link with respect to energy harvesting is investigated. We also propose a new design technique to improve the tolerance of a metal mountable tag toward the variations in the size of the metallic platform. Finally, we present a small slot antenna for metal mountable passive UHF RFID tags. It has an extremely small footprint of only 3×3 cm^2 (0.0915λ× 0.0915λ at 915 MHz) and slim structure (thickness 1.5 mm) based on only a single conductor layer. Measurements verified the new design technique and results showed that the tag achieved state-of-the-art performance.**

***Index Terms*—Radio-Frequency Identification, Metal mountable tag, Tag antenna, Slot antenna, Mutual polarization efficiency, Antenna spatial coverage**

I. INTRODUCTION

Radio-frequency identification (RFID) technology provides compelling means for the automatic identification and tracking of items. This is achieved by labeling them with battery-free remotely addressable electronic tags composed of an antenna and an integrated circuit (IC). The use of propagating electromagnetic waves at ultra-high frequencies (UHF) for powering and communicating with the passive tags enables rapid interrogation of a large quantity of tags through various media from the distances of several meters. In comparison to bar-codes, RFID tags allow the data stored in them to be updated wirelessly at any time. These are the main advantages that initially sparked the interest on passive UHF RFID systems. For more information on RFID technology, we refer firstly to two landmark papers [1] [2] presenting early investigations. A survey of the history of RFID is presented in [3][4] and a comprehensive introduction to today's systems and standardization is provided in [5][6][7]. Finally, a thorough discussion of the design of antennas for RFID tags can be found in [8][9].

A special feature in the design of antennas for RFID tags is that they need to be interfaced directly to an ultra-low-power RFID application specific integrated circuit (tag IC). The impedance of a tag IC is largely determined by the charge pump in the chip frontend [10]. It is a non-linear device and makes the IC impedance capacitive (example of a typical value: 15−j150 Ω). Therefore, the design of complex conjugate impedance matching for tag antennas is fundamentally different compared with conventional antennas which are commonly matched to 50 Ω.

Perhaps the greatest challenge yet to be overcome in the design of tag antennas is the undesired antenna-matter interaction, as in practice RFID tags are mounted on platforms with unspecified material properties. This is a particularly pronounced issue when tags are mounted on conductive items. The requirement of low-profile antenna structure leads to a situation where the separation of the antenna from a conductive surface is much less than a quarter wavelength. Hence, the antenna current flows predominantly horizontal to a conductive surface. In this configuration, the antenna operation is strongly influenced by the conductor [11]. Indeed, if the proximity of a conductive body is omitted in the design, the tag is likely not functional at all when mounted on a conductive item.

For dipole-like antennas, which are the most popular type of antennas used in RFID tags, this is explained by considering a line source parallel to a conductive plane. The electromagnetic boundary conditions require that the tangential electric field at the surface vanish. This means that there is a current on the surface with almost equal magnitude, but approximately opposite phase compared with the source current. Thus, the superposition of the radiation generated by the two current distributions approximately cancels out in the far field. Consequently, the antenna radiation efficiency will be low.

Alternatively, the image theory can be used to understand the phenomenon. In this case, an identical antenna (image source) is placed at an equal distance on the opposite side of the conductive plane which is assumed to have infinite extent. The plane is then removed, but its impact is modelled by feeding the image source antenna in such a way that the original boundary condition at the conductive plane is satisfied (the tangential electric field vanishes). This is achieved with an image source antenna carrying a current with equal magnitude but opposite phase compared with the primary source antenna. Theory of antenna arrays can then be used to find the far field radiation pattern. The computation of input impedance of the coupled antennas reveals that for very closely-spaced antennas the mutual resistance approaches the self-resistance [12]. This means that the coupled antennas become approximately short-circuited. Consequently, even small loss resistance will degrade the radiation efficiency. The antenna directivity, however, may be enhanced. In practice, the proximity of a conductive body (even a small one compared with the antenna) can greatly affect the antenna radiation pattern and the antenna impedance is a function of the distance to the metal [13].

Recalling the top priorities in the design of antennas for RFID tags; cheap and unobtrusive structure, it is evident that addressing the fundamental limitations on the antenna size-performance ratio and the adverse effects due to the proximity of conductive bodies jointly, presents a prominent challenge. This makes it extremely difficult to achieve the high tag read ranges of several meters, while maintaining the antenna size and structural complexity at an acceptable level.

Nonetheless, conductive items of various shapes and sizes are encountered through the whole spectrum of RFID applications. Examples include industrial asset management, machine inventory at construction sites, tracking of containers, vehicles and train cars through a transportation chain, monitoring of elevators and escalators, and item level identification of small metallic items, such hardware tools, kitchen ware, tin cans and spray bottles. Thus, the need for tag antennas performing well in the proximity of conductive bodies is eminent. Correspondingly, a great amount of research on such antennas has been conducted while the interest in the topic remains high [14]. Driven by the stringent requirements on tag size, cost, and integration, the focus of the research on antennas for metal mountable RFID tags has been shifting from the large rugged antennas with multiple conductor layers and vias toward structurally simpler antennas based on a single conductor layer. This type of antennas will be the focus of this work.

II. TAG READ RANGE AND COVERAGE

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. Assuming free-space conditions for site-independent comparison, the attainable tag read range in the directions ϕ and θ of a spherical coordinate system centered at the tag is given by [15]

$$d_{tag}(\phi,\theta)=\frac{\lambda}{4\pi}\sqrt{\frac{\chi_{pol}(\phi,\theta),\tau e_{r,tag}D_{tag}(\phi,\theta)EIRP}{P_{ic0}}};\quad\text{(1a)}$$

$$\tau=\frac{4\,\mathrm{Re}(Z_{tag})\mathrm{Re}(Z_{ic})}{\left|Z_{tag}+Z_{ic}\right|^2},\quad\text{(1b)}$$

where λ is the wavelength of the reader's carrier signal, $EIRP$ is the regulated equivalent isotropic radiated power, P_{ic0} is the wake-up power of the tag IC, χ_{pol} is the mutual polarization power efficiency between the tag and reader antennas, $e_{r,tag}$ is the tag antenna radiation efficiency, D_{tag} is the tag antenna directivity, and τ is the antenna-IC power transfer efficiency determined by the antenna and IC impedances Z_{tag} and Z_{ic}, respectively. Equation (1a) is a direct implication of Friis' simple transmission equation.

Typically, d_{tag} is reported assuming ideal mutual polarization efficiency ($\chi_{pol}=1$). Sometimes $\chi_{pol}=0.5$ is imposed to estimate the polarization loss between the predominantly linearly polarized tag antennas and circularly polarized reader antennas. However, with the help of today's computational electromagnetic tools, a more accurate estimate can be computed and also the spatial properties of the polarization efficiency can be studied.

The electric field of an electromagnetic plane wave impinging upon the tag can be expressed as [16]

$$\mathbf{E}=E_u\hat{\mathbf{u}}+E_v\hat{\mathbf{v}}=E_u\left(\hat{\mathbf{u}}+\gamma_l\hat{\mathbf{v}}\right)\quad(2)$$

where $\hat{\mathbf{u}}$ and $\hat{\mathbf{v}}$ are the orthonormal basis vectors and the complex number γ_l is the linear polarization ratio. An alternative representation, which is often used in the analysis of antenna polarization properties, is a vector sum of the pure left and right hand circularly polarized fields given by [16]

$$\mathbf{E}=E_L\hat{\mathbf{L}}+E_R\hat{\mathbf{R}};\quad\begin{cases}\sqrt{2}\hat{\mathbf{L}}=\hat{\mathbf{u}}-j\hat{\mathbf{v}}\\ \sqrt{2}\hat{\mathbf{R}}=\hat{\mathbf{u}}+j\hat{\mathbf{v}}\end{cases}\quad(3)$$

where $\hat{\mathbf{L}}$ and $\hat{\mathbf{R}}$ are the orthonormal basis vectors. By introducing a complex number γ_c, which is defined as the circular polarization ratio, equation (2) can be rewritten as

$$\mathbf{E}=E_L\left(\hat{\mathbf{L}}+\gamma_c\hat{\mathbf{R}}\right).\quad(4)$$

By the definition of γ_c given in equation (4), for the pure left and right hand circular polarization, $|\gamma_c|=0$ and $|\gamma_c|\to\infty$, respectively. Moreover, by noticing that a purely linearly polarized wave satisfies $|\gamma_l|=0$ or $|\gamma_l|\to\infty$ in equation (2), comparison of the field decompositions given in equations (2) and (3) shows that for a linearly polarized wave $|\gamma_c|\to 1$. Finally, the mutual polarization efficiency between the incident wave and an antenna with an arbitrary elliptic polarization is given by [17]

$$\chi_{pol} = \frac{1+|\gamma_{inc}|^2|\gamma_{ant}|^2 + 2|\gamma_{inc}||\gamma_{ant}|\cos\Delta}{(1+|\gamma_{inc}|^2)(1+|\gamma_{tag}|^2)} \quad (5)$$

where γ_{inc} and γ_{tag} are the circular polarization ratios of the incident wave and the tag antenna, respectively, and Δ is the phase different between γ_{inc} and γ_{tag}. In the special cases of left and right hand circular polarization and linear polarization of the incident wave, the achievable mutual polarization efficiencies are

$$\chi_{LHCP} = \frac{1}{1+|\gamma_{tag}|^{-2}},\ \chi_{RHCP} = \frac{1}{1+|\gamma_{tag}|^{2}},\ \chi_{LP} = \frac{(1+|\gamma_{ant}|)^2}{2(1+|\gamma_{tag}|^2)} \quad (5)$$

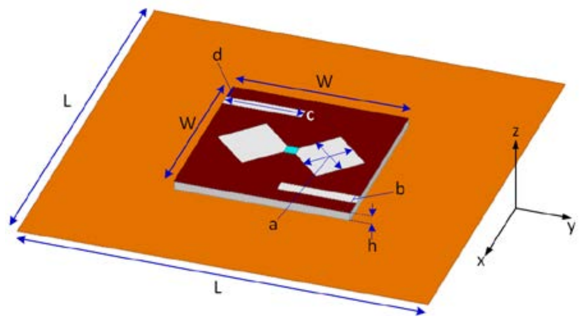
respectively. These values are attained when the tag is oriented with respect to the reader antenna so that $\cos\Delta = 1$.

In an RFID system, the mutual alignment of the reader and tag antennas is unspecified. Therefore, instead of just evaluating the achievable read range in a certain direction, a more holistic approach may be needed to measure the overall spatial coverage of the tag. This is a key-feature for the reliability of the energy harvesting. For this purpose, we define tag read range coverage C_α with $0 < \alpha < 1$ so that at $\alpha \cdot 100\%$ of the directions (θ, ϕ) it holds: $C_\alpha < d_{tag}(\theta, \phi)$. This means that when an incident field with the maximum regulated power density impinges upon the tag, i.e., when the maximum gain of the reader antenna is pointed toward the tag, there is higher than $\alpha \cdot 100\%$ probability that the tag can be detected at a distance longer than C_α, given that every mutual orientation between the antennas is equally likely. In practice, this is a reasonable assumption, since the items may arrive at an RFID read point in any orientation with respect to the reader antennas. The concept of tag read range coverage deepens in particular the analysis of metal mountable tags whose radiation properties are greatly affected by the size of the metallic platform the tag is mounted on.

III. Antenna Design and Simulation Results

Materials with high permittivity can be used to lower the antenna self-resonance frequency and thereby to reduce the physical size of the antenna [18]. This design technique was applied in the design of a metal mountable tag in [15], where a slot antenna was suspended on a ceramic Barium Titanate ($BaTiO_3$) substrate with high relative permittivity of approximately 39. The disk-shaped tag had the thickness of 2.9 mm and diameter of only 27.5 mm (0.084λ at 915 MHz). When mounted on metal surface, it achieved the read ranges of 1.2 m and 2.85 m on 3×3 cm^2 and 20×20 cm^2 metal plates, respectively, under the U.S. RFID emission regulation: EIRP = 4 W. Despite the competitive size-performance ratio, here the antenna thickness may still limit the use of this tag in some applications. In addition, there was an appreciable loss in the dielectric material, which limited the attainable performance.

In this work, we have studied a slot antenna on low-loss microwave laminate Arlon AD1000 with the dielectric properties $\tan\delta = 0.0023$ and $\varepsilon_r = 10.7$ and thickness of 59 mils



Geometrical parameters in millimeters.

a	b	c	d	h	W	L
8.93	2.25	13.5	3	1.50	30	Varies

Figure 1. Studied antenna structure.

(≈ 1.50 mm). In comparison with $BaTiO_3$, the relative permittivity of this material is much smaller, but still fairly high in comparison to plastics and most circuit board materials. This enabled us to achieve a compact footprint of 3×3 cm^2 in the final design. Moreover, the low dielectric loss compared with $BaTiO_3$ helped us to achieve longer read ranges compared with [15] even though the thickness of the antenna was reduced from 2.9 mm to 1.5 mm. In terms of unobtrusiveness, which is often a key-requirement for an RFID tag, this is a significant improvement.

A slot antenna exhibits an inductive impedance below the self-resonance frequency of the antenna. This means that conjugate matching to a capacitive tag IC can be established already at frequencies below the antenna self-resonance frequency. We used NXP UCODE G2iL series RFID IC with the wake-up power of −18 dBm (15.8 μW). Based on [19], we modelled the chip as a parallel connection of a resistance of 2.85 kΩ and capacitance of 0.91 pF. The model represents the IC input at the wake-up power of the circuit and it includes the parasitics arising from the antenna-IC joint. At the design frequency of 915 MHz, the impedance of the equivalent circuit is approximately 13−j190 Ω.

The antenna design was initiated with a balanced slot configuration shown in Fig. 1 with *c*=0 (no secondary slots). A similar antenna has been studied in [15], but due to the thinner substrate with lower permittivity used in the present work, we did not achieve comparable radiation efficiency and suitably high inductive input reactance for conjugate matching with the tag IC. To remedy this, we found the secondary slots defined with parameter *c* in Fig. 1 useful. As seen from Fig. 2, the slots perturbed the parasitic current induced in the metal plate, reducing the peak amplitude beneath the antenna terminals and the tip of the main slot (peak value reduced from 160 A/m to 130 A/m). Moreover, the addition of the secondary slot reduced the antenna self-resonance frequency from 1025 MHz to 955 MHz changing the antenna impedance from 1.8+j86 Ω to 13+j188 Ω at 915 MHz. In view of impedance matching, this change was toward favorable direction. The

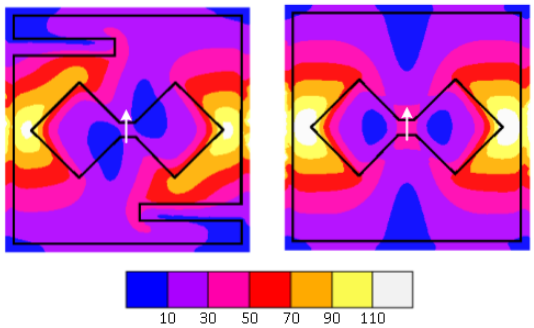


Figure 2. Surface current density amplitude [A/m] at 915 MHz on a 3.2 × 3.2 cm^2 copper plate beneath the antenna with (on the left) and without (on the right) the secondary slots. The antennas are accepting 100 mW power. The impressed source current is indicated with the arrows.

increase in resistance also correlated with the increase in the radiation efficiency, which increased from 0.016 to 0.023. As discussed in [15], it is difficult to meet the requirement of a slim and uniplanar structure with high radiation efficiency in the application of metal mountable tags. Nevertheless, the radiation efficiency of 0.023 is more than double of that achieved in [15] and corresponds with the attainable read range up to 2.5 meters. This is sufficient in many applications.

As the focus of this work is creating a small metal mountable tag, special attention was paid on the antenna performance on small metal plates. As shown in Fig. 3, with L = 3…3.8 cm, the frequency where d_{tag} peaks shift upwards as L is increased. This happened because the metal plate size affected the antenna impedance. On larger plates (L = 7…20 cm), the antenna impedance remained approximately constant, but the directivity increased with increasing L. This is seen in Fig. 3, where d_{tag} peaks at approximately 920 MHz for all plate sizes. The peak value increased up to L = 15 cm, but then started to reduce. This is because the diffraction fields from the plate edges add destructively in phase with the main beam radiation of the antenna. This agrees with the observation made earlier in [20].

As discussed above, the antenna operation is influenced by the size of the metal plate it is mounted on. To account for this in the design, we considered a number of different square

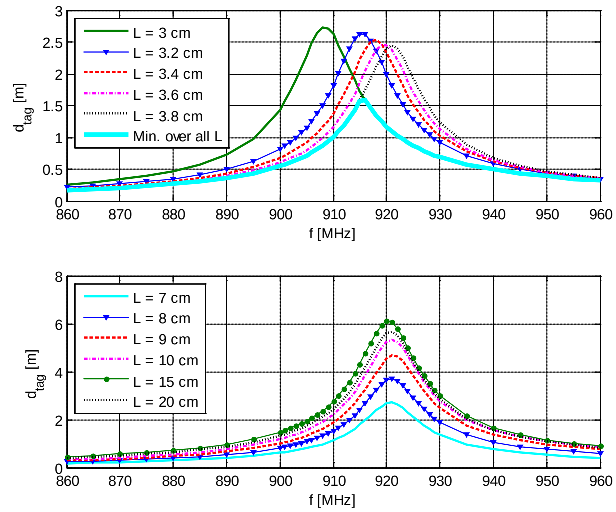


Figure 3. Attainable read range with linearly polarized reader antenna (EIRP = 4 W) in the direction normal to the metal plate.

metal plates and adapted the antenna for each one of them so that d_{tag} was maximum at 915 MHz. This yielded a set of prototype candidates. We then simulated each candidate on various metal plates with L = 3…20 cm to obtain a set of graphs similar to what is shown in Fig. 3. Finally, we chose the antenna for which the minimum of d_{tag} over all L peaked at 915 MHz with as high value as possible. The outcome is shown in Fig. 3 and the corresponding geometrical parameters are presented in Fig. 1.

In contrast to impedance and directivity, the antenna polarization was found to be unaffected by the metal plate size. Referring to the coordinate system in Fig. 1, , the polarization is strongly linear along the z-axis with the electric field vector contained in xz-plane. Figure 4 illustrates the attainable read range with different reader antenna polarizations in all spatial directions. The patterns are clearly different for different reader antenna polarizations. Since tag antennas are commonly linearly polarized, in the simplified link analysis it is often assumed that the use of circularly polarized reader antenna instead of a linearly polarized leads to mutual polarization power efficiency of 0.5 and,

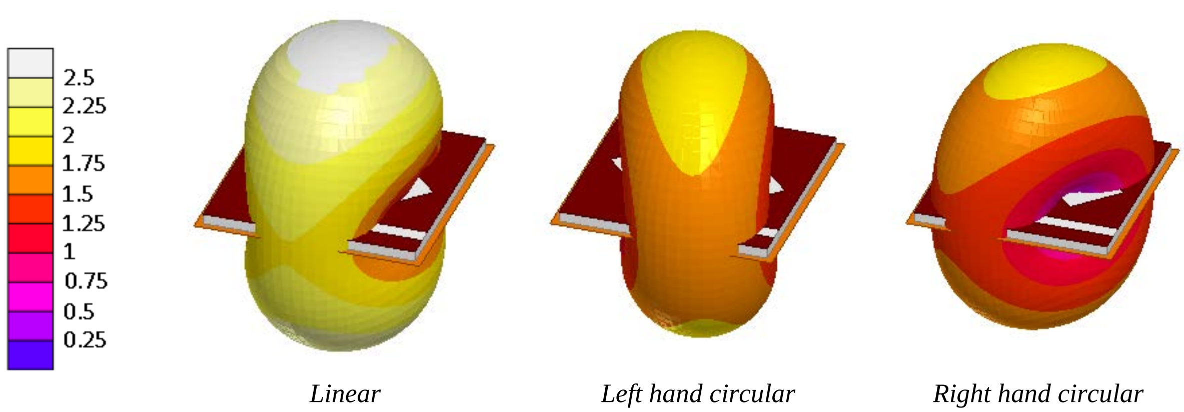


Figure 4. Attainable read range (EIRP = 4 W) in meters with different reader antenna polarizations at 915 MHz with the tag mounted on 3.2 × 3.2 cm^2 metal plate.

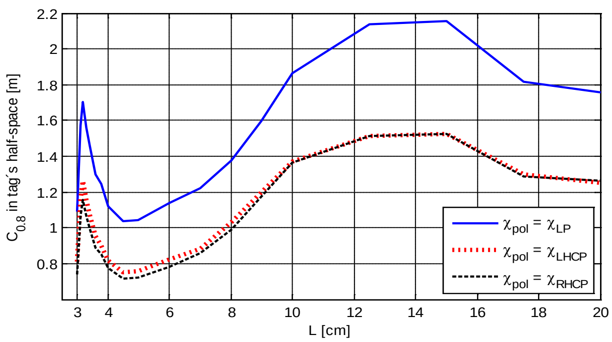


Figure 5. Attainable read range (EIRP = 4W) covering 80% of the spatial directions in the tag's half-space.

consequently, a reduction in d_{tag} by a factor of $\sqrt{0.5} \approx 0.71$. In our case, this also holds true along the z-axis, but not in all spatial directions, where the antenna is not purely linear. If neglected, this feature could lead, for instance, to unexpected results in radiation pattern measurements and overestimation of the attainable read range in certain spatial directions.

As discussed in Section II, an RFID tag is harvesting electromagnetic energy arriving from an unspecified source. Thus, instead of focusing only on the peak range range, looking at the overall spatial coverage may be more relevant. As metrics for this, in Section II we proposed the attainable read range coverage C_α so that in α·100% of the spatial directions it holds $C_\alpha < d_{tag}$. For metal-mountable tags, the impact of the size of the metallic platform on the coverage would be of particular importance. Also, since we do not expect that the tag would be read from behind the plate, especially on larger platforms, it is reasonable to limit the coverage analysis in the tag's half-space (the entire space excluding the directions behind the metal plate). Figure 5 shows C_α with α=80% for different reader antenna polarizations. It can be seen that the coverage is minimized in the transition from the smallest plate sizes influencing the antenna impedance to the larger plates, on which the antenna impedance remains approximitely constant, but the antenna directivty increases. This supports the new design technique discussed above, where the antenna is adapted to maximize the minimum of d_{tag} over all metal plates at the design frequency.

IV. Measurement Results and Discussion

Equation (1) shows explicitly how the electrical properties of the tag antenna and the impedance and wake-up power of the tag IC determine the read range. However, the measurement of small antennas is problematic [21]-[24] and accurate characterization of the non-linear IC frontend requires advanced equipment [25][26]. Thus, the required measured data to evaluate (1) is difficult to obtain. Also uncertainties may accumulate from the radiation pattern, antenna impedance, and tag IC measurements. Hence, the performance evaluation of fully assembled RFID tags based on the reader-to-tag communication threshold is advantageous. It avoids the separate antenna and IC measurements, correctly and automatically accounts for the IC mounting parasitics. Such measurement can be done with readers with adjustable output power and RFID testers [27]. We used Voyantic Tagformance measurement system.

The measurement is based on ramping down the transmission power of the reader during the interrogation of the tag under test. The lowest transmission power (threshold power: P_{th}) at which the tag remains responsive is recorded. In accordance with definitions in Section III, in the measurement we defined P_{th} with respect to the 'query' command in ISO 18000-6C standard. In addition, the wireless channel from the reader antenna to the location of the tag under test was characterized using a system reference with known properties. As detailed in [28], we then computed the attainable read range of the tag under test from

$$d_{tag} = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{\Lambda}\frac{P_{th*}}{P_{th}}}, \tag{6}$$

where P_{th} is the measured threshold power of the tag under test, Λ is a known constant describing the sensitivity of the reference tag, and P_{th*} is the measured threshold power of the reference tag.

As discussed in Section III the tag under test was found to be strongly linearly polarized in the direction normal to the metal plate. With this knowledge, it was aligned for polarization matching with the linearly polarized reader antenna used in the measurement. Similarly, we aligned the dipole type reference tag and thus the result shown in Fig. 6 is the attainable read range with a linearly polarized reader antenna. These results confirm the general trend of tag performance versus the metal plate size predicted by the simulations (see Fig. 3). As the plate size increases from L = 3 cm (the smallest plate the tag can fit on), the frequency where d_{tag} peaks shifts upwards and the peak value of d_{tag} reduces. The shift stops around L = 4 cm, where relative frequency difference is approximately 12 MHz and the peak value of d_{tag} has reduced around 30 cm in both simulation and measurement. On larger plates, the peak value of d_{tag} increases, but there is no frequency shift. This also agrees with the simulation.

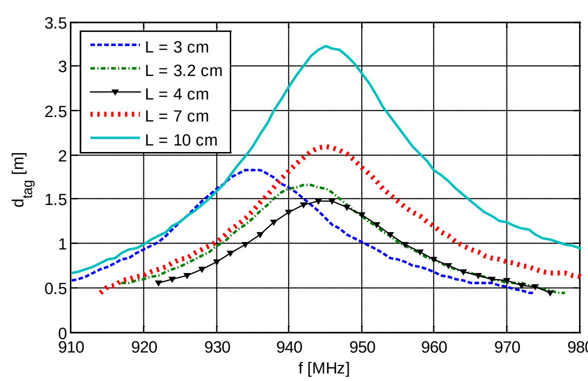


Figure 6. Measured attainable read range (EIRP = 4W) with a linearly polarized reader antenna in the direction normal to square metal plates of various sizes.

Table I. Comparison of metal mountable tags based on uniplanar antennas.

Ref.	[29]	[30]	[31]	[32]	[33]	[15]	[34]	This work
Tag size [mm³]	120×30 ×3.2	80.5×74.5 ×1.5	118×43 ×1.5	91×27 ×1	125×34 ×5	27.5Ø ×2.9	32Ø ×1.5	30×30 ×1.5
Metal plate [cm²]	20×20	31×23	31×23	NA	20×40	3×3 20×20	10×10	3×3 10×10
d_{tag}* [m]	8.9	11.2	13.4	6.7	22.1	1.2 2.85	2.65	1.8 3.2
Bandwidth	B	B	S	S	S	S	S	S

S = single-band, B = broadband, W = wideband

d_{tag}* [m] is the reported tag read range referred to $P_{ic0} = -18$ dBm and $EIRP$ =4 W under perfect polarization alignment.

The difference between the simulation and measurement was an upward frequency offset. On each metal plate, the measured d_{tag} peaked at an approximately 25 MHz higher frequency than in the simulation. We conjecture that this difference is due to variability of ±0.35, reported for the relative permittivity of the substrate, and due to possible air gaps between the metal plate and the tag. Based on the measurements, the peak values of d_{tag} were also smaller than in the simulation, which suggests that there may have been higher than expected dielectric loss in the substrate. Nevertheless, results attested the general trend in tag performance versus the metal plate size predicted by the simulations. This supports the new design technique for metal mountable tags for the identification of small conductive presented in Section III. Finally, as seen from Table I, the tested metal mountable tag achieved state-of-the-art size-performance ratio. In Table I, single band (S) tags are specifically designed for one of the global UHF frequency ranges. Broadband (B) tags achieve broader bandwidths of several tens of megahertz.

V. Conclusions

The metallic platform has a major impact on the performance of antennas in metal mountable UHF RFID tags. In this article, we focused on structurally simple antennas based on a single conductor layers. Our analysis showed that the size of the metallic platform had a strong influence on the antenna and this prompted a new design technique where the platform size is variable. With this method, we were able to improve the tag's tolerance toward variations in the platform size. Moreover, we showed how the full antenna radiation field data available in today's full-wave electromagnetic simulators significantly deepens the analysis of attainable read range coverage. This allowed us to judiciously assess the reliability of the tag's power harvesting capability without considering a fixed reader location.

Finally, we presented a small slot antenna for metal mountable passive UHF RFID tags. It had an extremely small footprint of only 3×3 cm² (0.0915λ×0.0915λ at 915 MHz) and slim structure (thickness 1.5 mm) based on only a single conductor layer. Measurements of the tag verified the new design technique and the results showed that the tag achieved state-of-the-art size-performance ratio

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