UHF RFID Reader Sensitivity Requirements Due to Poor Tag Matching

Abstract—**Passive ultra-high frequency (UHF) RFID systems are conventionally assumed to be downlink limited due to the relatively high power consumption of a tag's integrated circuit (IC). In this work, it is demonstrated that under certain conditions, tags' uplink/downlink losses become significantly asymmetrical, causing tens of decibels more loss in the uplink, thus making the system uplink limited. Our study reveals the necessity of developing RFID readers with higher sensitivity. It is shown that in extreme cases, the uplink loss can be 40 dB greater than in the downlink.**

Index Terms—**RFID tags, Radio-frequency identification, UHF antennas, UHF propagation**

I. Introduction

For ultra-high frequency (UHF) RFID systems, it is traditionally assumed that with today's state-of-the-art reader sensitivity (around -92 dBm [1]) and tag IC sensitivity (around -24 dB, [2], [3]), the range of the system is mainly downlink-limited due to the relatively high threshold power required to turn on the tag IC [4], [5]. Thus, efforts to extend the operation range of UHF RFID systems are mainly focused on designing efficient low-power tag ICs [2].

The above conclusion has an underlying assumption that the modulation loss of RFID tags is fixed and remains low compared to free-space path loss. However, in practical applications, tags can be placed in complex electromagnetic environments in which their performance can be significantly degraded. Two of the most common scenarios are:

- tags placed in close proximity to metallic surfaces.
- tags placed close to each other, such as along a hanging rail, forming an antenna array.

This paper demonstrates through theoretical analysis and full-wave simulation that in the above two scenarios, due to the alteration of tag antenna impedance, the modulation loss of tags becomes significantly greater, resulting in an asymmetrical reader to tag and tag to reader loss. Through full-wave simulations, it is shown that the additional loss in the uplink can be as large as 40 dB, resulting in an uplink-limited system.

The rest of this paper is organised as follows: Section II presents the theoretical analysis of the losses in RFID tags' link budget. A series of full-wave simulations are performed in section III. The results and analysis are given in section IV while a conclusion is presented in section V.

II. Theoretical Analysis

A passive UHF RFID tag switches between two impedance states Z_A and Z_B for backscatter modulation as shown in Fig. 1.

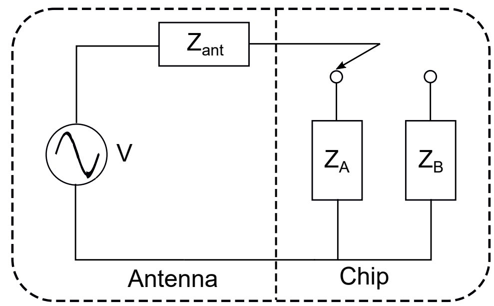

Fig. 1. The equivalent circuit of a passive UHF RFID tag

For the downlink, according to the Friis equation [6], [7], the power received by the tag, without considering the polarisation mismatch, is denoted by:

$$P_{tag} = \frac{P_{reader-tx} G_{reader-tx} G_{tag} \lambda^2 R_{down}}{(4\pi)^2 d^2} \quad (1)$$

where

$P_{reader-tx}$	– power input to the reader antenna
$G_{reader-tx}$	– gain of the reader transmit antenna
G_{tag}	– gain of the tag antenna
λ	– free space wavelength of the carrier wave
d	– distance from the reader antenna to the tag
R_{down}	– IC to antenna mismatch loss in the downlink

For the uplink, the received power of the reader receive antenna can be denoted by:

$$\begin{aligned} P_{rx} &= \frac{P_{reader-tx} G_{reader-tx} G_{reader-rx} G_{tag}^2 \lambda^4 R_{up}}{(4\pi)^2 d^4} \\ &= P_{reader-tx} L_{link} R_{up} \end{aligned} \quad (2)$$

where L_{link} represents the two way free-space loss plus antenna gains, while R_{up} denotes the uplink modulation loss.

Suppose that the tag operates in the impedance state Z_A to ensure maximum power delivery to its IC and changes to Z_B for the maximum reflection. The reflection coefficient for either state is defined as:

$$\Gamma_{A,B} = \frac{Z_{A,B} - Z_{ant}^*}{Z_{A,B} + Z_{ant}} \quad (3)$$

The downlink mismatch loss can thus be denoted as:

$$R_{down} = (1 - |\Gamma_A|^2) \quad (4)$$

For the uplink modulation loss, the voltages at the reader antenna terminal, corresponding to the two modulation states are:

$$V_A = \sqrt{P_{reader-tx} L_{link}} \Gamma_A \exp(j\phi) \quad (5)$$
$$V_B = \sqrt{P_{reader-tx} L_{link}} \Gamma_B \exp(j\phi) \quad (6)$$

Thus, the tag-modulated signal can be separated into a DC part (which is indistinguishable from environmental reflections) and the modulated data which can be represented as: $V_{DC} + V_{DATA}$ and $V_{DC} - V_{DATA}$, where

$$V_{DC} = \frac{1}{2}\sqrt{P_{reader-tx} L_{link}} (\Gamma_A + \Gamma_B) \exp(j\phi) \quad (7)$$
$$V_{DATA} = \frac{1}{2}\sqrt{P_{reader-tx} L_{link}} (\Gamma_A - \Gamma_B) \exp(j\phi) \quad (8)$$

The FM0 or Miller encoding ensures equal numbers of A and B states being transmitted. So, the uplink modulation loss is denoted by [8]:

$$R_{up} = \frac{|\Gamma_A - \Gamma_B|^2}{4} \quad (9)$$

For a typical passive UHF RFID tag IC, its two impedance states are usually capacitive due to the charge pump in its front end [9]. For instance, the impedance values for the EM4324 tag IC are [10]:

$$Z_A = 19 - j188\Omega \qquad @868\text{ MHz}$$
$$Z_B = 62 - j25\Omega \qquad @868\text{ MHz}$$

In the tag design process, to ensure maximum power delivery to the IC, the tag antenna impedance is designed to be conjugate-matched to Z_A [11], [12]. Thus, when the antenna is perfectly matched to the IC with an impedance at $19 + j188\Omega$, according to equations 4 and 9:

$$R_{down(dB)} = 0$$
$$R_{up(dB)} = 6.7 \quad (10)$$

Thus, even in a perfectly matched condition, the uplink loss is 6.7 dB higher than its downlink counterpart. Due to the high reader sensitivity which can be achieved with heterodyne detection, the system typically remains downlink limited.

However, in practical applications, tag antenna impedance can be severely affected by the environment, resulting in a match which is no longer the conjugate of Z_A. This increases the downlink loss due to power reflected from the antenna-tag mismatch and also results in an increased modulation loss in the uplink. The difference between the downlink and uplink loss against antenna impedance is shown in Fig. 2.

From Fig. 2, it is clear that the biggest difference occurs when the antenna resistance tends towards zero. The reactive component is less significant in this process. According to the antenna theory [6], an antenna's radiation resistance would significantly drop when it is placed close to metallic surfaces. This effect can be explained using the antenna array theory, together with the image theory: when an antenna is placed above a metallic plane, it can be viewed as placing an image source at the same distance but on the opposite side of the plane [6]. To satisfy the boundary condition at the surface of the metallic plane where no tangential electric field exists, the image source must have a current that is of equal magnitude but opposite phase, compared with the real source. As a result, according to the array theory, if both sources are close enough to each other, their far-field radiation would almost completely cancel out, leading to a radiation power P_{rad} that is almost zero [6]:

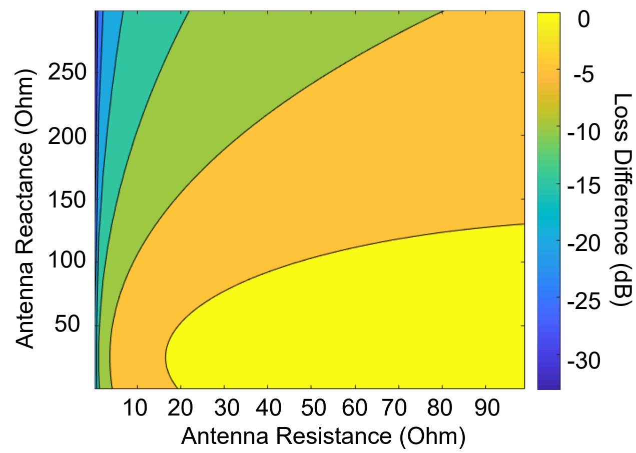

Fig. 2. Differences between the uplink and downlink reflection losses, at various antenna impedance values. A negative value means that uplink reflection loss is greater, vice versa.

$$P_{rad} = \frac{1}{2}|I_0|^2 R_r \quad (11)$$

A small radiation power means an almost zero radiation resistance, thus a close to zero real impedance for lossless antennas. In practical applications, this often happens when tags are attached to metal objects. Another scenario is when tags are in close proximity to each other, forming a linear antenna array in which the tag antenna's impedance could be considerably affected through a similar process.

As a result of these observations, common practical scenarios which degrade RFID tag performance have a much greater effect on the uplink, requiring a greater reader sensitivity than might otherwise be expected.

In the following section, a series of full-wave simulation is presented to verify the aforementioned assumptions.

III. Full-wave Simulation

A. Tag Design

We choose two types of tag design which are common and representative. For UHF RFID tags, the T-match is a well-known matching technique for making broadband dipoles [6], [12]. It has been widely adopted in commercial RFID tag design [13]–[15], and our results should apply to typical meandered and folded dipoles.

As shown in Fig. 3, a typical planar T-match antenna consists of a dipole of length l and width w, connected with another dipole of length a ($a < l$) and width w'. The two dipoles are separated from each other by a distance b. The T-match dipole is a balanced system which can be explained

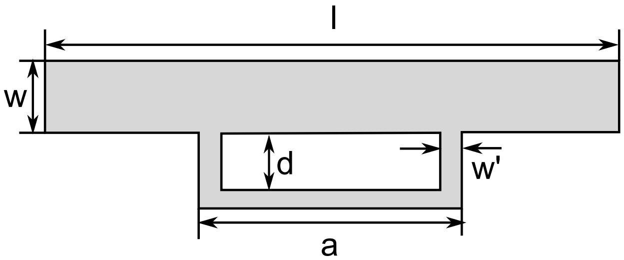

Fig. 3. A diagram of a typical planar T-match dipole

through the transmission line theory. The basic idea is to decompose the T-match into two modes: a) the transmission line mode which views the antenna as a shorted transmission line; b) the antenna mode which represents the antenna as two parallel dipoles. Details of these analyses can be found in [6]. Many commercial tags follow this design to enhance the bandwidth performance, with enhancements to meet a particular form factor (e.g. meander lines).

Parameters of the shorter dipole, a, b and $w^{'}$ can be adjusted to achieve a conjugate match to the tag IC's complex impedance in the energy harvesting state.

Besides the conventional T-match, we also use a special variant of T-match called embedded T-match in our simulations as shown in Fig. 4.

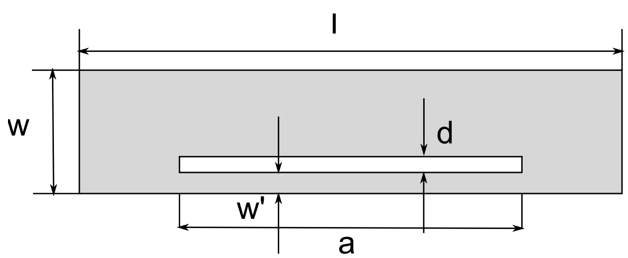

Fig. 4. A diagram of an embedded T-match dipole

Embedded T-match dipole has several advantages over its conventional counterpart as it is computationally easy to analyse, efficient in using space and has lower conductive losses near metal [16].

B. Simulation Procedures

The simulation procedures are listed as below:

- The total antenna width (including both dipoles of T-match) is fixed at 20mm. The antenna length is chosen to be 110mm and the slot width d is fixed to be 1mm.
- For both the conventional and embedded T-match, a parameter search is performed on the length a and width $w^{'}$ of the shorter dipole to match the input impedance to $Z_A^* = 19 + j188\Omega$ at 868 MHz.
- For the ground effect, the antenna is placed above an infinite perfect electrical conductor (PEC) plane with a distance ranging from 0.5mm to 15mm.
- For the array effect, a one-dimensional periodic boundary condition is applied, with the distance between elements ranging from 0.5mm to 15mm
- The uplink/downlink mismatch losses are obtained using the simulated antenna impedances, equations 4 and 9 and the Z_A, Z_B values given earlier.

In these simulations, a commercial full-wave simulation software (FEKO® [17]) is used. The antenna material is set to be copper with a thickness of 1 oz (0.0347mm), a typical value in PCB manufacturing. The simulation results are shown in Fig. 5 and processed in Fig. 6 and Fig. 7.

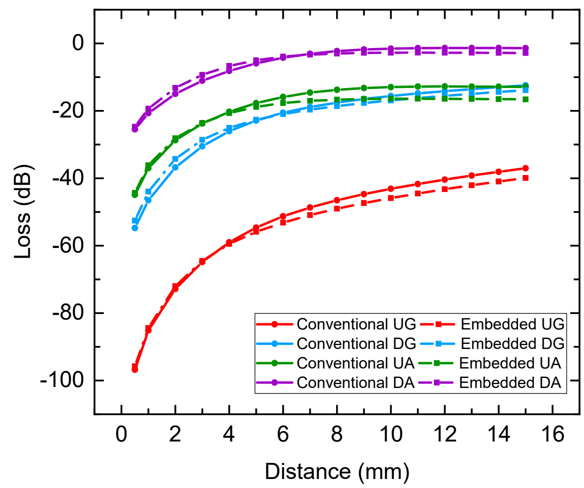

Fig. 5. Downlink (D) and uplink (U) losses for the 110 mm conventional T-match tag and embedded T-match tag against ground (G) or array (A)

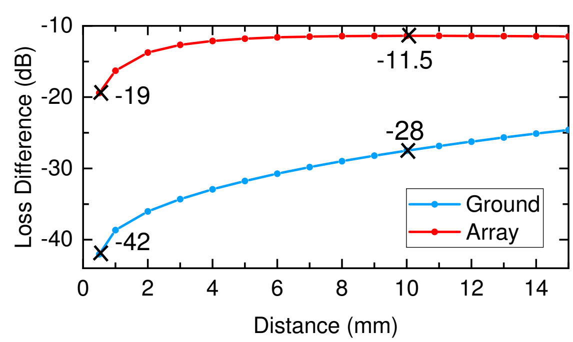

Fig. 6. Differences between the uplink and downlink loss for the conventional T-match tag at a length of 110 mm

From Fig. 6, it is clear that for the conventional T-match tag, at a close distance of 0.5mm to the metal ground, the uplink suffers from an additional loss of 42 dB compared to the downlink. Even at a moderate distance of 10mm, this value is still as high as 28 dB, sufficient to make the RFID system uplink-limited. For the array operation, the additional loss for the uplink is 20 dB at 0.5mm and 14 dB at 10mm, which is still considerably higher than the perfectly matched condition. A similar situation happens to the embedded T-match tag as shown in Fig. 7, leading to an excess loss of 43 dB and 29 dB

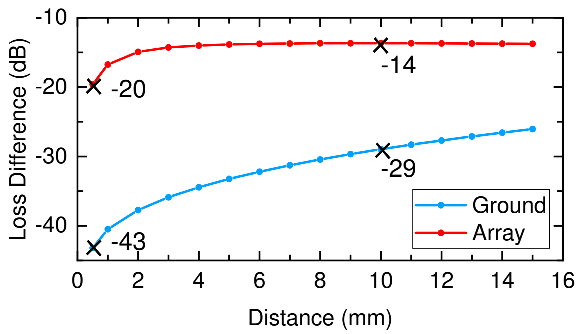

Fig. 7. Differences between the uplink and downlink loss for the embedded T-match tag at a length of 110 mm

when close to metallic surfaces while a loss of 20 dB and 14 dB occurs in the array configuration.

From the simulation results, we see that as opposed to traditional viewpoints, passive UHF RFID systems can become uplink limited when tags are placed near metal/close to each other, which is commonly found in practical applications. Moreover, with the improvement of tag IC sensitivity, the read ranges in most applications do not increase (e.g. in RFID portal gate applications). Instead, this improved sensitivity is utilised to make RFID tags smaller (thus lowering the cost) and to allow tagged items to be more densely placed, which in turn makes the proximity effect worse. This point has significant implications for current RFID systems as it means that RFID readers with higher sensitivities are needed, even in a short/moderate operation range.

For instance, consider the link budget for a 110 mm conventional T-match tag as shown in Fig. 6. When its distance to the ground plane is at 15mm, the downlink mismatch loss is around 12 dB, while the uplink loss is around 38 dB. For a transmitter with an effective isotropic radiated power (EIRP) of 36 dBm and a tag with a sensitivity of -20 dBm, this would mean a downlink budget of 56 dB, corresponding to a downlink limited range of around 4m for an isotropic tag. For a successful reading in the uplink, the reader sensitivity needs to be:

$$-20 - (56 - 12) - 38 = -102 \text{ dBm} \qquad (12)$$

In the industry, the reading sensitivity for the state-of-the-art reader is around -92 dBm [1], while the value for mainstream models are between -82 dBm and -86 dBm [18]–[20]. Thus, this value is lower than reader sensitivities available in the market, making the system uplink-limited. This problem could get worse with the increase of tag IC's sensitivity. In addition, when a tag is in close proximity to a metal ground plane/other tags, its gain pattern could be significantly altered, getting enhanced in some directions while reduced in other directions. This problem could cause a bigger challenge to the readers' sensitivities.

IV. Conclusion

This work shows through theoretical analysis and full-wave simulations that due to passive UHF RFID tags' unique impedance configurations, their uplink and downlink losses are asymmetrical. An additional loss of up to 40 dB in the uplink in practical applications can make the system uplink-limited as opposed to downlink limited, which is conventionally assumed. This finding reveals the necessity for developing RFID readers with a higher read sensitivity.

References

[1] Impinj. (2020) Impinj R700 RAIN RFID reader datasheet. [Online]. Available: https://support.impinj.com/hc/article_attachments/360012739479/Impinj_R700_RAIN_RFID_Reader_Datasheet.pdf

[2] G. D. Durgin, "RF thermoelectric generation for passive RFID," in *2016 IEEE International Conference on RFID (RFID)*, 2016, pp. 1–8.

[3] Impinj. (2020, may) Impinj m730 & m750 product brief / datasheet. [Online]. Available: https://support.impinj.com/hc/en-us/articles/360010797539-Impinj-M730-M750-Product-Brief-Datasheet

[4] D. Dobkin, *The RF in RFID: UHF RFID in practice*. Newnes, 2012.

[5] R. Chakraborty, S. Roy, and V. Jandhyala, "Revisiting RFID link budgets for technology scaling: Range maximization of RFID tags," *IEEE transactions on microwave theory and techniques*, vol. 59, no. 2, pp. 496–503, 2011.

[6] C. A. Balanis, *Antenna theory: analysis and design*. John wiley & sons, 2016.

[7] J. D. Griffin and G. D. Durgin, "Complete link budgets for backscatter-radio and RFID systems," *IEEE Antennas and Propagation Magazine*, vol. 51, no. 2, pp. 11–25, 2009.

[8] P. V. Nikitin, K. Rao, and R. D. Martinez, "Differential RCS of RFID tag," *Electronics Letters*, vol. 43, no. 8, pp. 431–432, 2007.

[9] G. De Vita and G. Iannaccone, "Design criteria for the RF section of UHF and microwave passive RFID transponders," *IEEE Transactions on microwave theory and techniques*, vol. 53, no. 9, pp. 2978–2990, 2005.

[10] E. M.-M. SA. (2012, aug) 1kbit read/write, ISO 18000-6C/EPC C-1 G-2 passive/battery-assisted contactless ic. [Online]. Available: http://www.advanide.com/wp-content/uploads/products/rfid/EM4324.pdf

[11] Impinj. (2017) RFID tag antenna design white paper. [Online]. Available: https://support.impinj.com/hc/article_attachments/360000130460/TagAntennaDesignOverview-20170606.pdf

[12] G. Marrocco, "The art of UHF RFID antenna design: Impedance-matching and size-reduction techniques," *IEEE antennas and propagation magazine*, vol. 50, no. 1, pp. 66–79, 2008.

[13] A. Technology. (2017, may) Aln 9740 squiggle (sq) higgs 4 datasheet. [Online]. Available: https://www.alientechnology.com/products/tags/squiggle/

[14] A. Technology. (2020, jan) Aln 9940 squiggle higgs 9 datasheet. [Online]. Available: https://www.rfid-alliance.com/RFIDshop/ALN-9940%20Squiggle%20Higgs-9%20(2020-01-21)%20.pdf

[15] A. Dennison. (2020, aug) Digital labeling technologies that optimize retail performance. [Online]. Available: https://rfid.averydennison.com/content/dam/rfid/en/products/rfid-products/data-sheets/RFID_Product_Portfolio_Joint_Digital.pdf#page=3

[16] D. D. Deavours, "Improving the near-metal performance of uhf rfid tags," in *2010 IEEE International Conference on RFID (IEEE RFID 2010)*. IEEE, 2010, pp. 187–194.

[17] E. S. . S.-S. P. Ltd. (2014, may) FEKO user manual. Accessed on: May 5, 2019. [Online]. Available: http://altairuniversity.com/wp-content/uploads/2015/03/UserManual.pdf

[18] Zebra. (2017) Fx7500 fixed RFID reader. [Online]. Available: https://www.zebra.com/gb/en/products/spec-sheets/rfid/rfid-readers/fx7500.html

[19] IMPINJ. (2019, may) Speedway R420 RAIN RFID reader. [Online]. Available: https://www.impinj.com/platform/connectivity/speedway-r420/

[20] Zebra. (2017) Fx9600 fixed UHF RFID reader. [Online]. Available: https://www.zebra.com/content/dam/zebra_new_ia/indesign-spec-sheets/fx9600-spec-sheet-en-us.pdf