A Practical Guide to Optimal Impedance Matching for UHF RFID Chip

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***Abstract*—This paper shows that the classical conjugate impedance matching used in the UHF RFID is not optimal anymore with new chips that have high sensitivity. The optimal matching allowing to maximize the read range of an RFID system (reader and tag) is introduced. The principle relies on finding the optimal trade-off between the power received by the tag and the modulated power backscattered to the reader. This matching depends on both tag and reader parameters. The proposed method is optimal and can be applied to any tag (passive and semi-passive). Compared to classical conjugate impedance matching, we show that this new approach can increase the read range by 22% and 8% in two examples: for a semi-passive tag based on Monza X8-K Dura chip and a passive tag based on Monza R6-P chip, respectively. Finally, a practical guide is proposed for antenna designers to optimize the matching in practical applications.**

***Index Terms*—Delta RCS, impedance matching, read range, RFID.**

I. Introduction

Antenna matching in UHF RFID has gathered a significant attention among the RFID community. This problem has a central place for any tag designer since the overall performance of the RFID system largely depends on the matching between the tag antenna and the chip. Thus, any improvement in the techniques used to realize this impedance matching can lead to a general improvement of the performance in any RFID system.

Basically, the matching in RFID differs from classical matching used in RF since no additional components are added between the antenna and the chip. Instead, the tag antenna is designed to match directly the chip impedance (without any matching network). This technique allows one to minimize the final cost of the tag which can be as low as 10 cents and also simplify tag manufacturing. However, a significant care during the antenna design should be taken since the matching depends on the considered chip characteristics.

During the years, many researchers have proposed a wild variety of antennas to realize the matching between the tag antenna and the chip in order to maximize the performance [1] such as T-match [2]–[4], inductively coupled loop [5] and nested slot [6].

However, since passive UHF tags do not include any battery to operate, the objective of the matching remains identical in almost all tag designs and corresponds to the maximization of the power received by the chip (in a given bandwidth and/or for a given effective permittivity range).

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While this design represents the optimal solution to improve the reading distance for low sensitivity passive tags (*i.e.*, where read range is limited by the tag sensitivity), more sensitive tags (*e.g.*, semi-passive tags) are not limited by this constraint. Additionally, between 2005 [7] and 2020 [8] chip sensitivity has been improved by about 15 dB, which represents an improvement of approximately 1 dB per year. New passive chips are now achieving a sensitivity close to -23 dBm [9]. On the other side and between 2006 [10] and 2020 [11], fixed reader sensitivity has been increased by 10 dB, however many handheld readers remain with lower sensitivities. Thus, read range of a classical RFID system can now be also limited by the reader sensitivity. Consequently, an antenna design based on conjugate matching may not be optimal anymore with semi-passive chips and new sensitive passive chips since characteristics of the reader are not taken into account on the overall performance. This statement is even more true given that the tag chip performance improves faster than the reader chip performance.

Several articles in the literature have pointed out the non-optimality of the conjugate matching. However, only few articles have proposed different matching techniques. An interesting article [12] proposes a maximization of the read range by realizing a trade-off between the received power and the modulated power. The authors succeed to express this maximization as an optimization based problem. However, their results remain strongly dependent of the modulator architecture. More recently, authors in [13] introduced a graphical representation to characterize the performance of an RFID system. The chart presents the average transmission coefficient as a function of the modulation efficiency. Optimal points allowing one to balance the received power and the modulation efficiency are extracted but the determination of the corresponding antenna impedance remains complex. Other articles have also mentioned scenarios where conjugate matching is not optimal [14].

The contribution of this article is to present the optimal procedure allowing to match an RFID chip to its antenna to maximize the read range. This optimal procedure is based on the determination of the trade-off between the power received by the chip and the modulated power backscattered towards the reader. The proposed matching is function of the tag and reader characteristics and allows one to maximize the read range of any tag (passive and semi-passive). This article is an extended version of conference paper [15]. Compared to [15], the analytic expression for the differential matching is derived and presented which makes the optimal matching exact and easy to implement. Moreover, a practical guide is proposed to help tag designers to optimize the tag antenna in order to

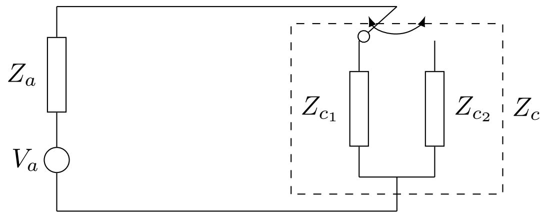

Fig. 1. Equivalent circuit of an antenna loaded by a RFID chip.

reach a given read range in a given bandwidth or given set of effective permittivity. The procedure can easily be extended to optimize the performance of a UHF for any parameter of interest.

The paper is organized as follows. Section II presents the classical matching techniques used in the literature and introduces the optimal matching. Section III establishes the performance of the optimal matching and provides a comparison with the previous techniques. Finally, Section IV presents the procedure to optimize the matching when multiple parameters are considered. The procedure aims to provide a guide to any tag designer to maximize the read range of a tag for a particular application.

II. RFID Impedance Matching

This section presents the two classical matching procedures allowing one to maximize the received power and the delta Radar Cross Section (RCS). Finally, the third one is built upon the two previous methods and represents the contribution of the paper. For all the methods, the impedance of the chip is supposed to be known and fixed.

A. Conjugate Matching

Conjugate matching allows one to find the antenna impedance Z_a which maximizes the power received by the chip of impedance Z_{c1}. This condition can easily be obtained by expressing the current flowing into R_a (see Fig. 1) as a function of the reflection coefficient:

$$I = \frac{V_a}{Z_a + Z_{c1}} = \frac{V_a}{2R_a}\left[1 - \rho_1\right] \tag{1}$$

where V_a is the open circuit voltage present at the antenna port and ρ_1 is the reflection coefficient, defined as [16]:

$$\rho_1 = \frac{Z_{c1} - Z_a^*}{Z_{c1} + Z_a} \tag{2}$$

From (1), the maximization of the power delivered into Z_{c1} can be obtained if the antenna impedance is equal to:

$$Z_{af} = Z_{c1}^* \tag{3}$$

which means that Z_a should have the same real part but an opposite imaginary part compared to Z_{c1}. This complex conjugate matching, well known in physics and engineering, is described extensively in the literature and represents the basis of every tag design.

When the tag sensitivity is the limiting factor of the RFID system, the forward read range can be extracted from the general Friis equation and is given by:

$$d_f = \frac{\lambda}{4\pi}\sqrt{\frac{P_r G_r G_t p \tau_1}{S_c}} \tag{4}$$

where P_r and G_r are the transmitted power and gain at the reader and G_t and S_c are the antenna gain and chip sensitivity at the tag side. Polarization loss factor is p, and:

$$\tau_1 = 1 - |\rho_1|^2 = \frac{4R_{c1}R_a}{|Z_{c1} + Z_a|^2} \tag{5}$$

which represents the transmission coefficient between the antenna and the chip (in the default state). Finally note that the maximization of the forward read range defined by (4) is obtained for an antenna impedance equal to Z_{af}.

B. Differential Matching

Delta RCS is a quantity allowing one to characterize the efficiency of the backscatter modulation [17]:

$$\sigma_d = \frac{\lambda^2 G_t^2}{4\pi}\frac{|\rho_1 - \rho_2|^2}{4} \tag{6}$$

Note that this delta RCS can also be defined for any backscatter modulation [18]. Moreover, from (6), the delta RCS value can be improved by increasing the distance between ρ_1 and ρ_2 in a Smith chart [19].

Maximization of (6) can be obtained by injecting (2) into (6) and then differentiated with respect to R_a and X_a. The resolution leads to a system of two non-linear equations [15]. Lukas W. Mayer succeeded to derive the exact analytic solution of such antenna impedance in his PhD thesis [20]:

$$R_{ar} = \sqrt{R_{c1}R_{c2}\frac{(R_{c1} + R_{c2})^2 + (X_{c1} - X_{c2})^2}{(R_{c1} + R_{c2})^2}} \tag{7}$$

$$X_{ar} = -\frac{R_{c2}X_{c1} + R_{c1}X_{c2}}{R_{c1} + R_{c2}} \tag{8}$$

This condition depends on the impedance values in both states and leads to the maximization of the delta RCS for a given chip.

When the reader sensitivity is the limiting factor of the RFID system, the round-trip read range can be extracted from a modified form of the radar equation and is given by [21]:

$$d_r = \sqrt[4]{\frac{P_r G_r^2 \lambda^2 p^2 \sigma_d}{(4\pi)^3 S_r}} \tag{9}$$

where S_r is the reader sensitivity. Finally, a tag designed with an antenna of impedance Z_{ar} allows one to maximize (9) and represents the best approach for tags which are not limited by the activation power (*e.g.*, semi-passive tags). Differential matching (which maximizes (9)) and conjugate matching (which maximizes (4)) can be seen as two opposite design procedures.

TABLE I
READ RANGE LIMITATION OF THE UHF RFID TECHNOLOGY.

Reader Sens.	Chip Sens.	Fwd. RR	R-T RR	Read Range
$-\infty$	S_c	d_f	∞	d_f
S_r	$-\infty$	∞	d_r	d_r
S_r	S_c	d_f	d_r	$\min(d_f, d_r)$

C. Optimal Matching

Optimal matching allows any tag designer to jointly optimize the power received by the tag and the backscattered power received at the reader to maximize the read range. Before introducing this new matching, let's considers two hypothetical cases which will help us to understand the full picture. First, assuming an infinitely sensitive reader, one can remark that the associated read range is only limited by the forward read range. This read range is given by (4) and can be maximized using the conjugate matching. Second, assuming an infinitely sensitive tag, one can remark that now, the read range is only limited by the round-trip read range. This second read range is given by (9) and can be maximized using the differential matching. These two cases are presented in the two first lines of Table I.

In the general case, read range of a passive tag can be limited by both the forward read range and the round-trip read range. This read range of RFID system always corresponds to the minimum between the read range given by the Friis equation [see (4)] and the read range given by the radar equation [see (9)]:

$$d_o = \min(d_f(Z_a), d_r(Z_a)) \tag{10}$$

This case is presented on the third line of Table I and encompasses the previous two cases. Note that designing a tag to maximize the absorbed power (*i.e.*, with conjugate matching) or the modulated power (*i.e.*, with differential matching) results in a sub-optimal read range since both functions can not reach maximum at the same time. Fig. 2, which plots the forward read range given by (4) the reverse read range given by (9) as a function of Z_a, illustrates the described situation. Note that Z_{af} and Z_{ar} corresponds to the maximum of (4) and (9) respectively. However, in the case of Fig. 2, the maximization of (10) can not be achieved with Z_{af} or Z_{ar}.

Let's define Z_{ao} the optimal impedance allowing one to maximize (10). Before giving the procedure to determine Z_{ao}, let's first analyze the condition on Z_a for which the forward read range (4) (see blue curve on Fig. 2) is equal to the round trip read range (9) (see red curve on Fig. 2). By setting $d_f(Z_a) = d_r(Z_a)$, then taking the power of 4 and simplifying, one can obtain:

$$\frac{\lambda^2}{4\pi}\frac{P_r G_t^2 \tau_1^2}{S_c^2} = \frac{\sigma_d}{S_r} \tag{11}$$

Developing τ_1 and σ_d with (5) and (6) respectively leads to:

$$\frac{P_r 16 R_{c1}^2 R_a^2}{|Z_{c1}+Z_a|^4 S_c^2} = \frac{|\rho_1-\rho_2|^2}{4S_r} \tag{12}$$

Replacing ρ_1 and ρ_2 by their expressions and rearranging:

$$\frac{16 P_r S_r R_{c1}^2}{|Z_{c1}-Z_{c2}|^2 S_c^2} = \frac{|Z_{c1}+Z_a|^2}{|Z_{c2}+Z_a|^2} \tag{13}$$

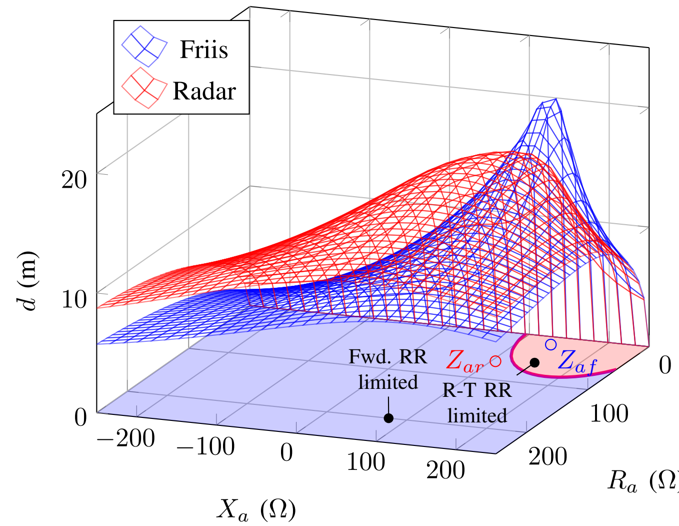

Fig. 2. Read range predicted by the Friis equation (in blue) and the radar equation (in red) as a function of R_a and X_a. Impedance values for which the Friis equation is lower than the radar equation are limited by the forward read range. Impedance values for which the radar equation is lower than the Friis equation are limited by the round-trip read range.

which can be rewritten as a function of R_a and X_a:

$$\frac{(R_{c1}+R_a)^2+(X_{c1}+X_a)^2}{(R_{c2}+R_a)^2+(X_{c2}+X_a)^2} = \frac{16 P_r S_r R_{c1}^2}{S_c^2 |Z_{c2}-Z_{c1}|^2} \tag{14}$$

where the second term is a scalar denoted K and only depends on the chip and the reader parameters. Rearranging (14) leads to:

$$\left(R_a + \frac{R_{c1}-KR_{c2}}{1-K}\right)^2 + \left(X_a + \frac{X_{c1}-KX_{c2}}{1-K}\right)^2 = r_\circ^2 \tag{15}$$

which corresponds to a circle of center $(R_\circ, X_\circ) = (-(R_{c1} - KR_{c2})/(1-K), -(X_{c1} - KX_{c2})/(1-K))$ and radius $r_\circ$ defined as:

$$r_\circ = \sqrt{\left|\frac{R_{c1}^2+X_{c1}^2-K(R_{c2}^2+X_{c2}^2)}{1-K} - \left(\frac{R_{c1}-KR_{c2}}{1-K}\right)^2 - \left(\frac{X_{c1}-KX_{c2}}{1-K}\right)^2\right|} \tag{16}$$

Thus, the intersection between the forward read range and the round trip read range represents a circle in the impedance plane (see the magenta circle in Fig. 2).

Moreover, note that for $K > 1$, the read range defined by (10) is limited by the forward read range inside the circle and by the round trip one outside the circle. On the other side, if $K < 1$, the read range is limited by the round-trip read range inside the circle and by the forward read range outside the circle (see Fig. 2).

The exact procedure to determine the value of Z_{ao} analytically can now be presented. This procedure only depends on the impedance Z_{af} [see (3)], Z_{ar} [see (7) and (8)] and the circle [see (14)]. In the most general case, only three cases can be distinguished:

Algorithm 1 Impedance matching procedure to maximize the read range of a UHF passive tag.

Require: Z_{c1}, Z_{c2}, S_c, S_r, P_r
  Compute Z_{af} with (3)
  Compute Z_{ar} with (7) and (8)
  Compute K with (14)
  Compute $R_\circ$, $X_\circ$ and $r_\circ$ with (15) and (16)
  if Z_{af} and Z_{ar} are inside the circle **then**
    if $K \geq 1$ **then**
      $Z_{ao} = Z_{af}$
    else
      $Z_{ao} = Z_{ar}$
    end if
  else if Z_{af} and Z_{ar} are outside the circle **then**
    if $K \geq 1$ **then**
      $Z_{ao} = Z_{ar}$
    else
      $Z_{ao} = Z_{af}$
    end if
  else
    Compute A, B and C with (22)
    Compute θ_o with (23)
    Compute Z_{ao} with (24)
  end if

If Z_{af} and Z_{ar} are both inside the circle, then Z_{ao} can be obtained with:

$$Z_{ao} = \begin{cases} Z_{af} & \text{if } K \geq 1 \\ Z_{ar} & \text{if } K < 1 \end{cases} \tag{17}$$

If Z_{af} and Z_{ar} are both outside the circle, then Z_{ao} is equal to:

$$Z_{ao} = \begin{cases} Z_{ar} & \text{if } K \geq 1 \\ Z_{af} & \text{if } K < 1 \end{cases} \tag{18}$$

If Z_{af} and Z_{ar} are inside and outside the circle (Z_{af} inside and Z_{ar} outside, or, Z_{af} outside and Z_{ar} inside), then the maximum of (10) has to lie on the circle. and can be expressed by the maximization of (10) under the constraint $d_f(Z_a) = d_r(Z_a)$. Note that in this case, this problem is equivalent to the maximization of either τ_1 [see (5)] or $|\rho_1 - \rho_2|^2$ [see (6)] under the same constraint. Choosing (5) as the objective function leads to:

$$\begin{aligned} Z_{ao} = \max_{R_a, X_a} \quad & \frac{4R_{c1}R_a}{(R_{c1}+R_a)^2 + (X_{c1}+X_a)^2} \\ \text{s.t.} \quad & \begin{cases} \frac{(R_{c1}+R_a)^2+(X_{c1}+X_a)^2}{(R_{c2}+R_a)^2+(X_{c2}+X_a)^2} - K = 0 \\ R_a \geq 0 \end{cases} \end{aligned} \tag{19}$$

Note that, in this case, the read range is simultaneously limited by the Friis equation and the radar equation. This optimization problem can be easily solved by open source solvers like IPOPT in CasADi [22].

Moreover, due to the simple form of the constraint, analytic solution can also be determined by parametrizing the constraint with a new variable θ:

$$\begin{cases} R_a = R_\circ + r_\circ \cos\theta \\ X_a = X_\circ + r_\circ \sin\theta \end{cases} \tag{20}$$

Re-injecting (20) into the objective function of (19) and then differentiating with respect to θ, extremums of the objective function can be determined by finding the roots of:

$$A\cos\theta + B\sin\theta = C \tag{21}$$

with A, B and C real numbers equal to:

$$\begin{cases} A = -2r_\circ R_\circ (X_\circ + X_{c1}) \\ B = -r_\circ[(R_\circ + R_{c1})^2 + r_\circ^2 + (X_\circ + X_{c1})^2 - 2R_\circ(R_{c1} + R_\circ)] \\ C = 2r_\circ^2(X_\circ + X_{c1}) \end{cases} \tag{22}$$

Note that (21) admits two solutions, noted $\theta_{o1,2}$, which correspond respectively to one maximum and one minimum:

$$\theta_{o1,2} = \pm\arccos\left(\frac{C}{\sqrt{A^2+B^2}}\right) + \arctan\left(\frac{B}{A}\right) \tag{23}$$

Note that a significant care must be taken to the sign of A and B to estimate $\theta_{o1,2}$. Finally, real part and imaginary part of Z_{ao} can be determined:

$$\begin{cases} R_{ao} = R_\circ + r_\circ \cos(\theta_{o1,2}) \\ X_{ao} = X_\circ + r_\circ \sin(\theta_{o1,2}) \end{cases} \tag{24}$$

Note also that the solution with a negative real part has to be discarded since antenna should always satisfy $R_a > 0$.

The complete procedure is summarized in Algorithm 1 and is also available as an Octave/Matlab script [23]. Note that this procedure can be applied to any RFID system and only depends on Z_{c1}, Z_{c2}, S_c, S_r, P_r. An antenna designed with the impedance Z_{ao} allows a tag designer to maximize the read range by taking into account both reader and tag characteristics. Moreover, the procedure remains valid in any propagation environment other than free space (*i.e.* with reflections, multipath, etc.) as long as the channel is reciprocal.

III. Numerical Application

A. Parameters of the study

Three chips are considered to evaluate the performance of the different matching techniques. All chip characteristics are presented in Table II. The first chip is a low sensitivity chip (released in 2006), the second one is optimized for semi-passive mode (released in 2012) and the last one is a high sensitivity chip (released in 2017). Note that chip sensitivity and chip impedance in the default state have been extracted directly from their respective published datasheets. However, datasheets do not usually present the chip impedance in the second state Z_{c2}. Estimation of Z_{c2} can still be realized based on the chip architecture which classically uses a FET transistor in parallel with the rectifier circuitry. Thus Z_{c2} can be estimated by considering the equivalent impedance composed of Z_{c1} in parallel with the resistance R_{mod} of the transistor [24]:

$$Z_{c2} = \frac{Z_{c1}R_{mod}}{Z_{c1} + R_{mod}} \tag{25}$$

Even if the modulation resistance depends on the technological process used during the chip design, we assume the same $R_{mod} = 50\ \Omega$ for all the chips. Note that more accurate estimation for a given chip can be realized by measuring

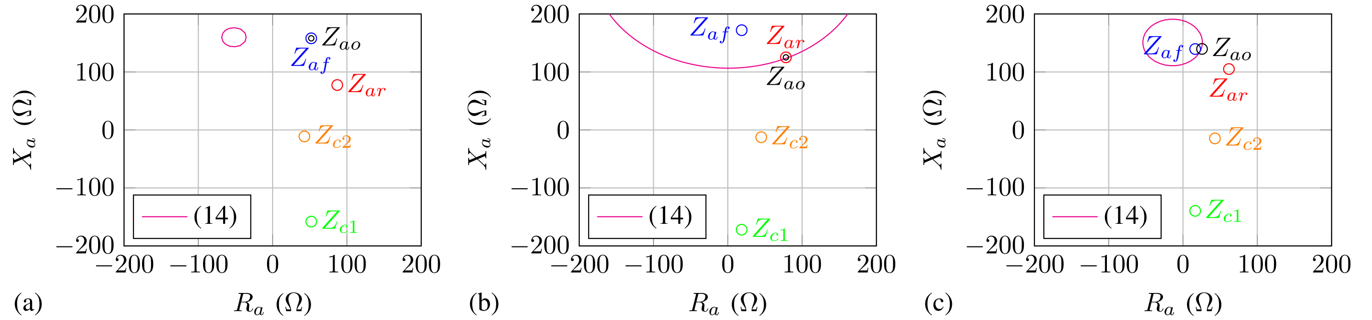

Fig. 3. Impedance matching maximizing the read range for (a) Impinj Monza 2 chip ($K = 0.013$), (b) Impinj Monza X-8K chip ($K = 0.39$) and (c) Impinj Monza R6-P chip ($K = 0.083$).

TABLE II
UHF RFID CHIP PARAMETERS AT 915 MHZ.

Chip	S_c (dBm)	Z_{c1} (Ω)
Impinj Monza 2	-11.5	$52 - j158$
Impinj Monza X-8K	-24	$18.7 - j172$
Impinj Monza R6-P	-20	$16.4 - j139.5$

the second state impedance using a dedicated measurement bench [25].

For the reader side, we consider a monostatic reader with a transmitted power of $P_r = 30$ dBm, an antenna gain of $G_r = 6$ dBi and a sensitivity $S_r = -75$ dBm.

B. Optimal Matching

Performance of the optimal matching is presented in Fig. 3 for the three different chips. Note that the position of Z_{ao} for each chip has been done by applying Algorithm 1. The procedure allows one to maximize the read range by finding the best trade-off between the power received by the tag and the modulated power received by the reader.

From Fig. 3(a), we can see that the Monza 2 chip is characterized by a Z_{af} and a Z_{ar} both outside the circle. Since $K = 0.013$, the read range is limited by the Friis equation outside the circle. Thus the optimal impedance matching for this chip (and the considered reader) is the complex conjugate.

For the Monza X-8K Dura chip, Fig. 3(b) presents a situation where both Z_{af} and Z_{ar} lie inside the circle. In this case $K = 0.39$, which indicates that the read range inside the circle is limited by the radar equation. Thus the optimal matching corresponds to the differential matching.

Finally, for the Monza R6-P chip (see Fig. 3(c)), Z_{af} is inside the circle and Z_{ar} outside. In this situation, optimal impedance matching can not be achieved by Z_{af} nor Z_{ar} but should lie on the circle. The exact position can be determined by solving the optimization under constraint using (19) (or by computing (22), (23) and (24)). Note that for this Z_{ao} value, both forward and round trip read range are equal.

C. Performance Comparison

Table III presents a comparison to the performance of all presetented matching: conjugate matching (Z_{af}), differential matching (Z_{ar}) and optimal matching (Z_{ao}), for all considered chips in free space. One can easily check that conjugate matching is able to maximize the power received by the chip (*i.e.*, $\tau_1 = 1$) whereas differential matching is able to maximize the modulated power received by the reader (*i.e.*, σ_d). Note that in all cases, optimal matching is able to maximize the read range of the RFID system by realizing the best trade-off between the received power (at the chip) and the modulated power (at the reader). The associated read ranges for each chips are equal to 7.9 m, 23.6 m and 20.6 m for the Monza 2, Monza X-8K Dura and the Monza R6-P, respectively.

Note also that for semi-passive tags (*e.g.*, based on a Monza X-8K chip) or for passive tags with high sensitivity (*e.g.*, based on a Monza R6-P chip) the read range associated by the optimal matching can be increased by 22% and 8% respectively compared to classical conjugate matching. This gain can simply be obtained by optimizing the antenna to achieve an impedance equal to Z_{ao} instead of Z_{af}. Finally, the presented method can be entirely applied analytically.

TABLE III
PERFORMANCE OF MONZA 2, MONZA X-8K DURA AND MONZA R6-P CHIP UNDER DIFFERENT MATCHING CONDITIONS

MONZA 2						
	Z_a (Ω)	τ_1	σ_d (cm^2)	d_f (m)	d_r (m)	d (m)
Z_{af}	$52 + j158$	1	40.7	7.9	18.2	7.9
Z_{ar}	$87.0 + j77.5$	0.70	68.7	6.6	20.8	6.6
Z_{ao}	$52 + j158$	1	40.7	7.9	18.2	7.9

MONZA X-8K DURA						
	Z_a (Ω)	τ_1	σ_d (cm^2)	d_f (m)	d_r (m)	d (m)
Z_{af}	$18.7 + j172$	1	50.9	33.4	19.3	19.3
Z_{ar}	$78.2 + j125$	0.51	114	23.7	23.6	23.6
Z_{ao}	$78.2 + j125$	0.51	114	23.7	23.6	23.6

MONZA R6-P						
	Z_a (Ω)	τ_1	σ_d (cm^2)	d_f (m)	d_r (m)	d (m)
Z_{af}	$16.4 + j139.5$	1	49.0	21.1	19.1	19.1
Z_{ar}	$61.8 + j105$	0.56	102	15.7	23.0	15.7
Z_{ao}	$23.9 + j137$	0.96	67.4	20.7	20.7	20.7

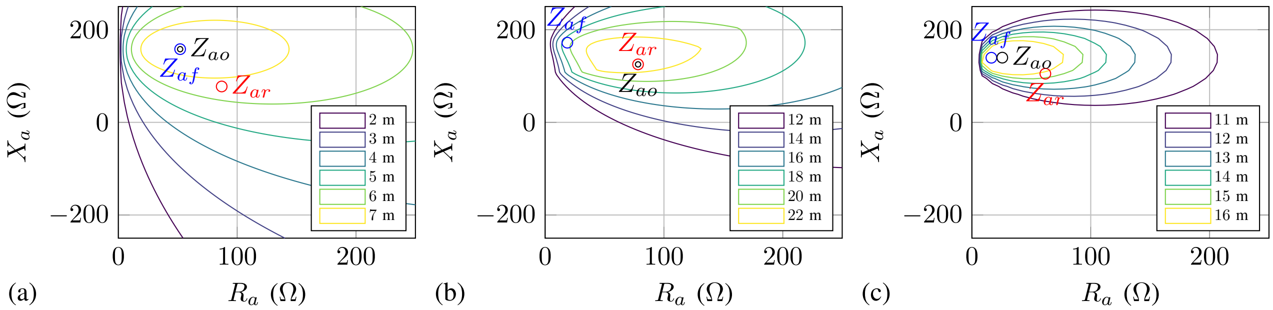

Fig. 4. Target impedance set for a given read range for (a) Impinj Monza 2 chip, (b) Impinj Monza X-8K chip and (c) Impinj Monza R6-P chip.

IV. Practical Considerations

Section III has presented the optimal matching for a given set of parameters (single frequency, single effective permittivity). In real applications, a tag antenna is usually not designed with these single parameter values. Instead, tag designers prefer to sacrifice the optimality to ensure an acceptable performance over a given bandwidth or/and several materials, *i.e.*, over a given effective permittivity range.

The proposed method can actually be easily adapted to ensure a given performance (*i.e.*, read range) for different parameter values. In the following part, we present the design of an RFID tag antenna allowing to achieve a read range of 16 m in the full UHF bandwidth (860–960 MHz) and over an effective dielectric permittivity range from 1 to 1.5. Moreover, this approach can be applied to any chip. Finally, note that this procedure can easily be adapted by any tag designer to take into account different and multiple constraints.

The general idea of the procedure is: assuming that the tag antenna gain is known and constant, determine the set of impedance allowing to achieve a given read range. Knowing this set, antenna impedance has to be designed to ensure that its impedance remains into the corresponding set for all possible constraints. This technique then guarantees that the corresponding read range is equal or higher than the given read range.

In the following, this technique is applied on the proposed example. From (10), the sets of Z_a values for constant read range, can be represented graphically. Impedance values inside a given set have a higher read range compared to the objective read range and then satisfy, by definition, the constraint. Fig. 4 presents the contours of (10) for the three different chips (and by considering $G_r = 6$ dBi and $G_t = 2.15$ dBi). The shape of a set is close to an ellipse. Actually, if the RFID system is only limited by the forward read range, the shape is an exact ellipse and has been first described in [26]. Note that, by taking into account round-trip read range, the final shape is not an ellipse anymore. Note that this set is always centered on Z_{ao} which represents the optimal matching for a given chip (see Section III). This optimal point can correspond to Z_{af} [see Fig. 4(a)], Z_{ar} [see Fig. 4(b)] or none of the above [see Fig. 4(c)].

From this target impedance set, a tag designer can now design an antenna whose impedance lies into the corresponding set for all considered frequencies (860–960 MHz) and all considered effective permittivity (1 to 1.5). Note that this optimization procedure is actually general and can be applied to any parameter.

A. Antenna Structure

In the following, we consider the tag antenna as a dipole and a T-match is used to realize the matching between the antenna and a Monza R6-P chip. Note that the approach is not limited to this antenna design but can be applied to any classical structures *i.e.*, T-match, inductively coupled loop and nested slot (with or without size reduction techniques such as meandering).

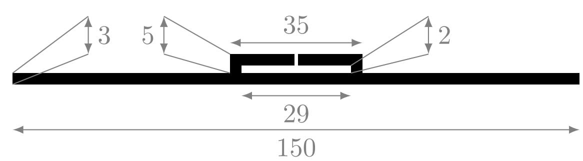

Fig. 5. Considered antenna structure: classical T-match. Dimensions are in mm.

The structure of the antenna is presented in Fig. 5. Simulation has been performed using CST using the time domain solver. The antenna is composed of infinitely thin planar perfect electric conductor. The antenna is immersed into medium with specific effective dielectric permittivity. Note that effective permittivity has been varied form 1 to 1.5 by step of 0.1 (by running 6 independent simulations). Final dimensions (in mm) of the antenna are reported directly in Fig. 5.

Reflection coefficient in the default state $|\rho_1|^2$ is presented in Fig. 6. We can see that $|\rho_1|^2$ values are low in the considered bandwidth and ranges from -5 to -15 dB in the considered bandwidth of 860 and 960 MHz. Note, for example, that a better matching is obtained for a permittivity of 1.5 at 980 MHz. But surprisingly, lower values inside the 860–960 MHz band, as we will see, represent the best trade-off to maximize the read range.

Delta RCS is presented in Fig. 7 for the same band and the same permittivity range. One can remark that the corresponding delta RCS values belong in the interval $[-19; -23]$ dBsm in the 860–960 MHz band. These value are also lower compared to the maximum theoretical values of -22.4 and -16.4 dBsm which can be obtained by a perfect passive and

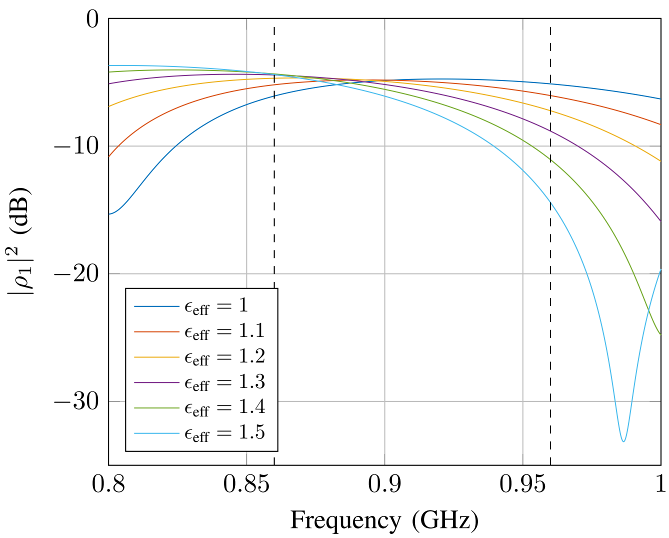

Fig. 6. Reflection coefficient as a function of the frequency for different effective dielectric permittivity values.

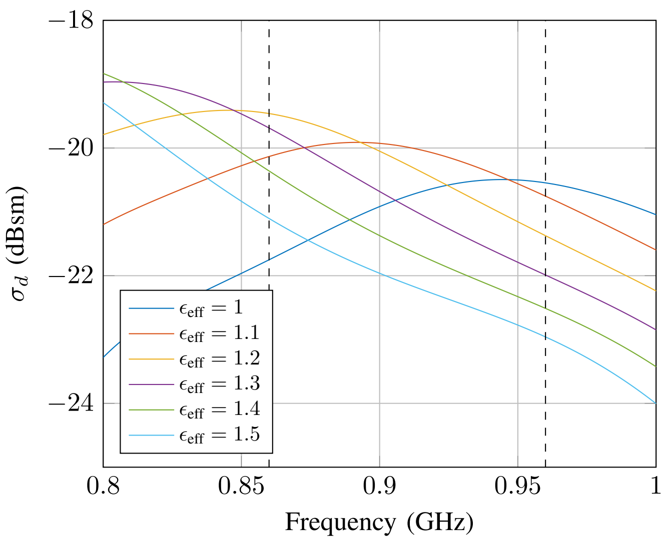

Fig. 7. Delta RCS as a function of the frequency for different effective permittivity values.

semi-passive tag respectively. But here again, as we will see, the values presented in Fig. 7 represent the best trade-off to maximize the read range.

B. Results

Results for the proposed tag (based on a Monza R6-P chip and the antenna presented in Fig. 5) are finally presented in Fig. 8. Note that curves associated to the right legend in Fig. 8 are identical to the ones in Fig. 4(c) and represents the impedance value achieving a given read range (assuming $G_r = 6$ dBi and $G_t = 2.15$ dBi). Each curve associated to the left legend corresponds to a simulation between 860 and 960 MHz for a given effective permittivity.

First note that classical conjugate matching does not correspond to the optimal matching which maximize the read range since Z_{af} and Z_{ao} are distant form each other. While Fig. 6

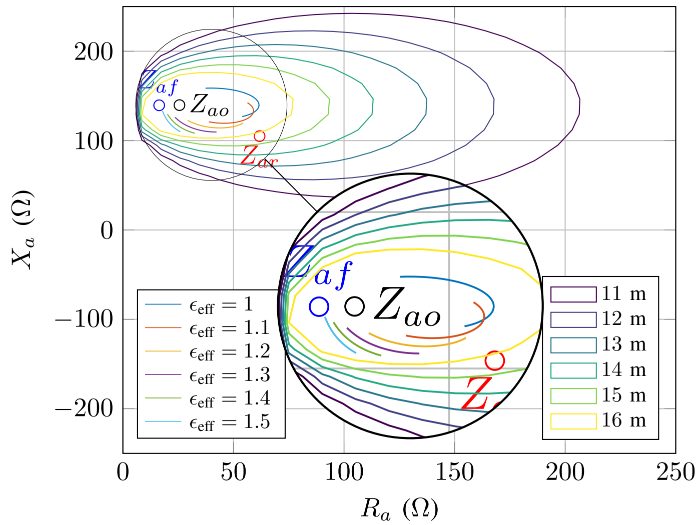

Fig. 8. Design of an antenna satisfying the optimal matching conditions for the Monza R6-P chip between 860 and 960 MHz ($G_t = 2.15$ dBi, constant Z_c). Left legend: antenna impedance for different dielectric permittivity. Right legend: target impedance set for a given read range for Impinj Monza R6-P chip.

and 7 have shown that perfect match and maximum delta RCS are not achieved in our band, Fig. 8 shows that these antenna impedance values achieve a good trade-off to maximize the read range since these value are very close to Z_{ao}. Moreover, assuming the same constant gain of $G_t = 2.15$ dBi for the whole bandwidth, we can check that all impedance values lie inside the corresponding set corresponding to 16 m (see yellow ellipse in Fig. 8) and thus achieve a read range higher than 16 m for the whole frequency band and all permittivity values. This procedure allows one to simply optimize/validate an antenna in different operating condition (frequency band, effective permittivity range, etc.) and can be applied to any chip.

In the following, the performance of the proposed tag is validated in more accurate situation. Fig. 9 presents the simulated read ranges of the proposed tag and the same reader selected parameters for a given effective permittivity of $\epsilon_{\text{eff}} = 1$. Note that Fig. 9 takes into account the exact value of the antenna gain and the chip impedance for each frequency. The gain of the antenna has been extracted from the CST simulations whereas the impedance value has been extracted from the circuit present in the published datasheet [27, Fig. 4, p. 9] which consists of a resistance in parallel with a capacitance. Note also that the power dependency of the chip impedance is not taken into account but will be addressed in future work.

The forward read range [see (4)], the round-trip read range [see (9)] and the real read range defined [see (10)] can be compared over the whole band. Note that the reverse read range defined in the Voyantic Tagformance manual [28, Annex B.2, p. 146] and used in the Tagformance software is also plotted for comparison purposes. This reverse read range is defined as:

$$d_{rev} = \frac{\lambda}{4\pi}\sqrt{\frac{S_c G_r |\rho_1 - \rho_2|^2}{4 G_t \tau_1 S_r}} \tag{26}$$

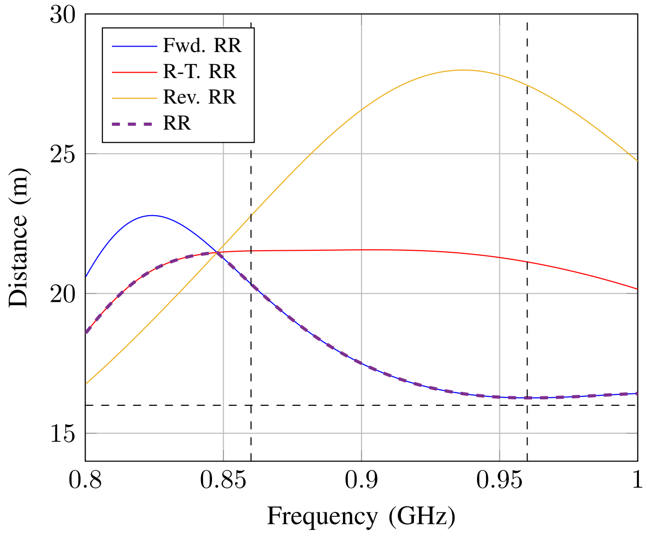

Fig. 9. Forward read range (Fwd. RR), round-trip read range (R-T RR) and real read range (RR) of the proposed tag in the band 800–1000 MHz and for an effective permittivity value of $\epsilon_{\text{eff}} = 1$ (simulated G_t and variable Z_c).

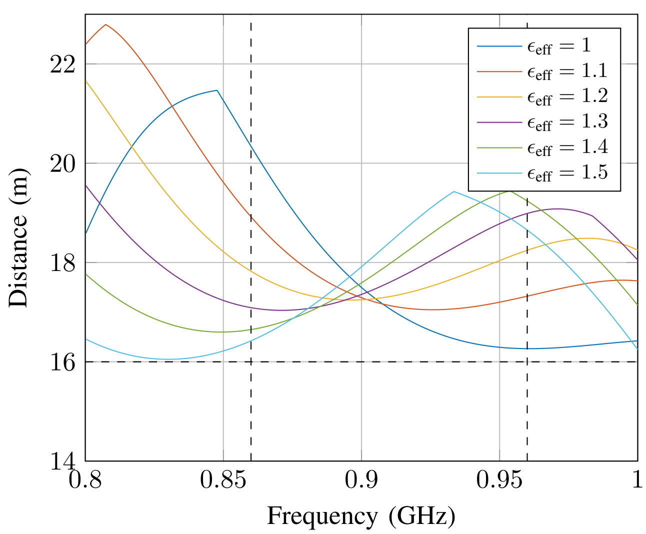

Fig. 10. Real read range of the proposed tag in the band 800–1000 MHz and for different effective permittivity values (simulated G_t and variable Z_c).

where the argument of the second term represents the ratio between the power on tag reverse times G_r, and the reader sensitivity. The reverse read range represent the distance at which the tag can be heard assuming that the tag is exactly at its threshold activation power. This quantity is different from the round-trip read range. The only case where the reverse read range is equal to the round-trip read range is at the activation power of the chip (see the intersection of the three curves). Moreover, we can see that for frequencies lower than 850 MHz the read range is limited by the round-trip read range whereas for frequencies above 850 MHz, the read range is limited by the forward read range.

The final figure presented in Fig. 10 presents the read range of the proposed tag for all the dielectric permittivity values. Note that the frequency dependency of both tag antenna gain and chip impedance are taken into account (power dependency is not considered). In all cases, we can easily check that the read range defined by (10) is, as expected, higher than the specified constraint of 16 m for the considered band of 860 – 960 MHz and for the considered effective permittivity range 1 – 1.5 which validates the proposed design.

V. Conclusion

This paper shows that the performance of the antenna matching in UHF RFID can still be improved compared to the classical conjugate matching used in the literature. This improvement can be done by considering both the power received by the tag and the modulated power received by the reader. The exact procedure allowing one to determine the antenna impedance as a function of the tag and reader parameters is presented using a simple geometrical concepts. This optimal matching allows any tag designer to maximize the read range of a UHF RFID system. Compared to conjugate matching, the reading distance associated with optimal matching can be improved by 22% and 8% for semi-passive tags based on Monza X Dura chip and passive tags based on Monza R6-P chip respectively. Finally, a practical guide is provided to realize the matching using the proposed technique when multiple constraints are considered, such as ensuring a certain read range in a specific band across several dielectric materials. We hope that this work can be used by other tag designers to optimize tag performance in terms of realistic system read range in practical situations.

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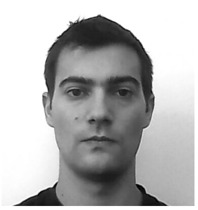

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