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# 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. Two new approaches are introduced to realize the impedance matching between a UHF chip and its antenna. The first method allows one to maximize the delta Radar Cross-Section (RCS) of any tag and corresponds to the optimal matching for semi-passive tags. This matching is only function of the two impedance states of the chip. The second method allows one to maximize the read range of any passive tag. The principle relies on finding the optimal trade-off between the received power by the tag and modulated power sent to the reader. This matching is function of the tag sensitivity and states, and the transmitted power and sensitivity of the reader. Compared to classical conjugate impedance matching, we show that these new approaches can increase the read range by 22% and 8% for a semi-passive tag based on Monza X8-K Dura chip and a passive tag based on Monza R6-P chip, respectively.

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

## I. INTRODUCTION

RFID technology enables significant improvement in any logistic chain by allowing an operator to identify dozen of tags per seconds at a distance higher than 10 m.

However, many factors have to be taken into account to evaluate the performance of a RFID system. Read range, for example, can be greatly affected by the mismatch between the antenna and the chip. Also, for UHF tags, impedance matching between the chip and the antenna, is done without additional components. This constitutes a major difference compared to classical Radio-Frequency (RF) circuits in which a matching network is used to interconnect different devices. In UHF RFID, tag antenna is designed specifically to match the chip impedance. This design ensures to minimize the cost of the tags since no additional components are added.

Due to the technological process, input impedance of a RFID chip is generally capacitive, thus, the impedance of the antenna has to be designed to be highly inductive. Over the years, different structures have been used to realized the matching [1] such as T-match [2]–[4], inductively coupled loop [5] and nested slot [6]. Note that in all these designs, the objective of the impedance matching is to maximize the power received by the chip (in a given bandwidth and/or for a given effective permittivity range). While this design was optimal to increase the read range for low sensitivity passive chips

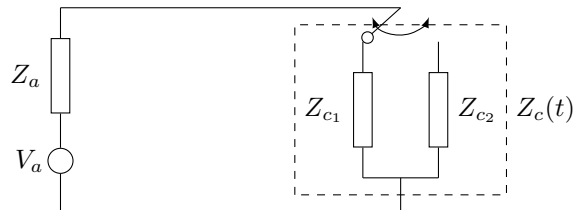


Fig. 1. Equivalent circuit of a minimum scattering antenna loaded by a RFID chip.

(*i.e.*, where read range is dictated by the tag sensitivity), semi-passive tags are not limited by this constraint. Additionally, since 2005 [7] and 2020 [8] chip sensitivity has been reduced by 15 dB, which represents an improvement of 1 dB per year. New passive chips are now achieving a sensitivity of  $-24$  dBm [8]. This trend will continue for future chip designs. In these two cases (semi-passive chips and new passive chips), read range can also be limited by the reader sensitivity, making the conjugate impedance matching non-optimal. Finally, and more importantly, optimal matching in these two cases is still unknown. The last affirmation also implies that performance of a RFID system can still be increased by carefully optimizing the matching between a RFID chip and its antenna.

The contribution of this article resides in two new approaches to realize the matching of a RFID chip to the antenna. The first approach, called differential matching allows the tag designer to maximize the delta RCS *i.e.*, the modulated power sent to the reader. This procedure only depends on the two impedance states and allows one to maximize the read range for any semi-passive tag. This approach is however not optimal for passive tags since the received power can be lower than the tag sensitivity. The second approach, called optimal matching, allows one to maximize the read range of any passive tag. This method is function of the tag and reader characteristics and is able to find the trade-off between the power received by the tag and the modulated power backscattered to the reader. This approach is optimal and allows one to maximize the read range of any passive tag.

The paper is organized as follows. Section II presents the conjugate matching, differential matching and optimal matching. Section III establish the performance of the different matching conditions for three different chips.

$$\begin{cases} 2R_a^4 + 2(R_{c1} + R_{c2})R_a^3 - 2((R_{c2}^2 + (X_a + X_{c2})^2)R_{c1} + (R_{c1}^2 + (X_a + X_{c1})^2)R_{c2})R_a - 2(R_{c1}^2 + (X_a + X_{c1})^2)(R_{c2}^2 + (X_a + X_{c2})^2) = 0 & (7a) \\ 4X_a^3 + 6(X_{c1} + X_{c2})X_a^2 + 2((R_{c1} + R_a)^2 + (R_{c2} + R_a)^2 + X_{c1}^2 + X_{c2}^2 + 4X_{c1}X_{c2})X_a + 2(X_{c1}X_{c2}^2 + X_{c2}X_{c1}^2 + (R_a + R_{c1})^2X_{c2} + (R_a + R_{c2})^2X_{c1}) = 0 & (7b) \end{cases}$$

## II. RFID IMPEDANCE MATCHING

The impedance values of a UHF chip depends on the technological process used by the manufacturer. Tag designer can usually not modify these values but can design a specific antenna to satisfy different constraints. In this section, we present three matching procedures allowing one to maximize the received power, the delta RCS and the read range. The first method corresponds to the classical matching used in the literature. The two latter ones are the contributions of the paper.

### A. Conjugate Matching

The objective of this matching is to maximize the power received at the chip terminals. This power can be derived from Fig. 1 where the antenna with an impedance  $Z_a = R_a + jX_a$  is connected to the chip in the default state of impedance  $Z_{c1} = R_{c1} + jX_{c1}$ .

The complex envelope of the current flowing into  $R_a$  can be written:

$$I(t) = \frac{V_a}{Z_a + Z_c(t)} = \frac{V_a}{2R_a} [1 - \rho(t)] \quad (1)$$

where  $\rho(t)$  is the reflection coefficient [9]:

$$\rho(t) = \frac{Z_c(t) - Z_a^*}{Z_c(t) + Z_a} \quad (2)$$

By computing the power dissipated into  $R_{c1}$  and then differentiating with respect to  $R_a$  and  $X_a$ , the condition to maximize the power dissipated into  $Z_{c1}$  can be expressed as:

$$R_{at} = R_{c1} \quad \text{and} \quad X_{at} = -X_{c1} \quad (3)$$

which means that the antenna impedance  $Z_a$  should have the same real part but an opposite imaginary part compared to the chip impedance. Note that this conjugate matching can simply be represented in a Smith chart and corresponds to a point  $\rho_1$  placed exactly at the center of the chart. Finally, this matching condition 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:

$$d_t = \frac{\lambda}{4\pi} \sqrt{\frac{P_r G_r G_t p \tau_1}{S_t}} \quad (4)$$

where  $P_r G_r$  is the effective isotropic radiated power of the reader and  $G_t$  and  $S_t$  are the tag gain and tag sensitivity respectively,  $p$  the polarization loss factor, and:

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

which represents the mismatch between the antenna and the chip (in the default state). Finally, a tag designed with an antenna of impedance  $Z_{at}$  allows one to maximize (4).

### B. Differential Matching

Delta RCS has been introduced in [10] and extended in [11]. This quantity corresponds to the variation of the backscattered field due to the antenna mode [9] and is proportional to the modulated power backscattered by the tag towards the reader:

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

Note that (6), as remarked in [10], is valid for all antennas (and not only for minimum scattering antennas). From (6), we can see that the delta RCS can be increased by increasing the distance between  $\rho_1$  and  $\rho_2$  in a Smith chart. At 915 MHz, (6) predicts a maximal delta RCS for passive (*e.g.*,  $\{\rho_1 = 0; \rho_2 = -1\}$ ) and semi-passive (*e.g.*,  $\{\rho_1 = +1; \rho_2 = -1\}$ ) UHF tags of  $-22.4$  dBsm ( $57.5$  cm<sup>2</sup>) and  $-16.4$  dBsm ( $230$  cm<sup>2</sup>) respectively. However, for real RFID chips,  $Z_{c1}$  and  $Z_{c2}$  are never perfect loads, thus (6) predicts a lower delta RCS value.

In order to maximize the delta RCS with respect to  $Z_a$ , (2) has to be injected into (6) and then differentiated with respect to  $R_a$  and  $X_a$ . Maximization of (6) can thus be transformed into the resolution of a system of two non-linear equations, see (7a) and (7b). First equation has only one root (subject to  $R_a > 0$ ). Second equation has one or three real solutions depending on the sign of the discriminant.

Even if analytical solutions for this system can not be easily expressed, simple cases can be highlighted. From (7b), if  $R_{c1} = R_{c2}$ , and if discriminant of (7b) is negative (*i.e.*, only one real solution), then  $X_{ar}$  can be obtained with:

$$X'_{ar} = -\frac{X_{c1} + X_{c2}}{2} \quad (8)$$

From (7a), assuming  $X_{ar}$  known,  $R_{ar}$  can always be obtained with:

$$R'_{ar} = \sqrt[4]{(R_{c1}^2 + (X_{c1} + X_a)^2)(R_{c2}^2 + (X_{c2} + X_a)^2)} \quad (9)$$

Note that even if  $R_{c1} \neq R_{c2}$ , antenna impedance  $Z'_{ar}$  obtained using (8) and (9) can still be used to approximate  $Z_{ar}$ .

Accurate solution in the general case can be found based on numerical approaches such as the trust-region dogleg algorithm [12], [13]. Solutions with  $R_a < 0$  should be rejected and can be avoided by carefully choosing the initial point. Solution(s) of (7a) and (7b) allow(s) one find  $Z_{ar} = R_{ar} + jX_{ar}$  to maximize the delta RCS of any 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 [14]:

$$d_r = \sqrt[4]{\frac{P_r G_r^2 \lambda^2 p^2 \sigma_d}{(4\pi)^3 S_r}} \quad (10)$$

where  $S_r$  is the reader sensitivity. Finally, a tag designed with an antenna of impedance  $Z_{ar}$  allows one to maximize (10).

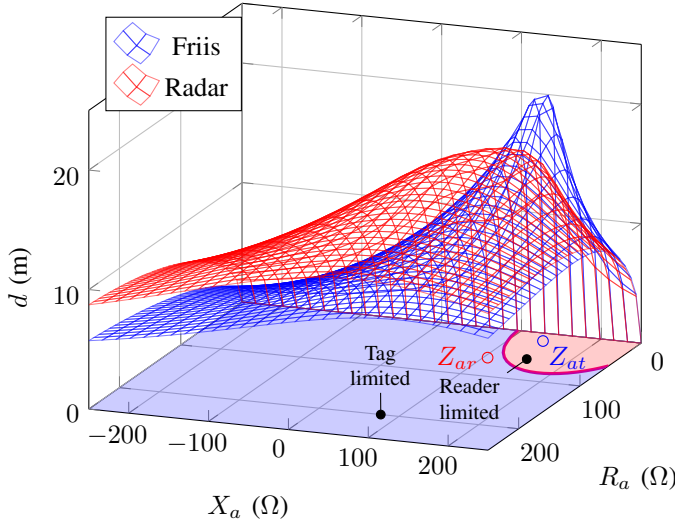


Fig. 2. Read range predicted by the Friis equation and the Radar equation as a function of  $R_a$  and  $X_a$ . Read range corresponds to the minimum of the forward and round-trip read range.

This matching is optimal for semi-passive tags (*i.e.*, tags which are not limited by the activation power). Differential matching can be seen as the opposite of the conjugate matching.

### C. Optimal Matching

Read range of a passive tag can be limited by either the tag sensitivity or the reader sensitivity and real read range of a RFID system 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 (10)]:

$$d_o = \min(d_t(Z_a), d_r(Z_a)) \quad (11)$$

Note that designing a tag to maximize the absorbed power or the modulated power results in a sub-optimal read range since both functions can not be maximum at the same time. Typical situation is presented in Fig. 2 which plots the read range given by (4) and (10) as a function of the antenna impedance. The read range of a RFID system corresponds, for a given  $Z_a$  value, to the minimum between  $d_t(Z_a)$  and  $d_r(Z_a)$  [see (11)]. As seen in Section II-A, maximization of (4) corresponds to the complex conjugate matching (see  $Z_{at}$  in Fig. 2). Furthermore, and as seen in Section II-B, maximization of (10) (or the delta RCS) corresponds to differential matching (see  $Z_{ar}$  in Fig. 2). However, the maximization of the read range [defined as (11)] does not always corresponds to  $Z_{at}$  nor  $Z_{ar}$ .

Thus, a trade-off exists and allows one to maximize (11) and achieve a read range which can be higher than the one obtained with  $Z_{at}$  and  $Z_{ar}$ . The maximization of (11) corresponds to an optimal  $Z_a$  value, called in the following  $Z_{ao}$ . The procedure is more complex than the two previous approaches however, interesting properties can be used to solve the problem exactly.

First note that, the condition where the read range is limited by both reader and tag sensitivity can be obtained by finding

the condition on  $Z_a$  for which  $d_t(Z_a) = d_r(Z_a)$ . Replacing  $d_t(Z_a)$  and  $d_r(Z_a)$  by their expressions (4) and (10) leads to:

$$\frac{(R_{c1} + R_a)^2 + (X_{c1} + X_a)^2}{(R_{c2} + R_a)^2 + (X_{c2} + X_a)^2} = \frac{16P_r S_r R_{c1}^2}{S_t^2 |Z_{c2} - Z_{c1}|^2} \quad (12)$$

where the second term is an important constant, denoted  $K$  in the rest of the paper, which only depends on the chip and the reader parameters. Note also that (12) does not depend on the wavelength  $\lambda$ , reader antenna gain  $G_r$ , tag antenna gain  $G_t$  and the polarization loss factor  $p$ . Rearranging (12) leads to:

$$\left(R_a + \frac{R_{c1} - KR_{c2}}{1 - K}\right)^2 + \left(X_a + \frac{X_{c1} - KX_{c2}}{1 - K}\right)^2 = r_o^2 \quad (13)$$

where we can now easily recognize the equation of a circle with center  $(R_o, X_o) = (-(R_{c1} - KR_{c2})/(1 - K), -(X_{c1} - KX_{c2})/(1 - K))$  and radius  $r_o$ . Thus, the set of  $Z_a$  values where the (general) Friis equation and the (modified) Radar equation are equal, represents a circle in the complex plane. This circle is plotted in magenta in Fig. 2, and has a significant importance for correctly matching the RFID chip to its antenna. Moreover, one can also remark that if  $K > 1$ , values of  $Z_a$  inside the circle correspond to  $d_r(Z_a) > d_t(Z_a)$  which means that read range is limited by the tag sensitivity inside the circle and by the reader sensitivity outside the circle. Furthermore, if  $K < 1$ , values of  $Z_a$  inside the circle correspond  $d_t(Z_a) > d_r(Z_a)$  which means that read range is limited by the reader sensitivity inside the circle and by the tag sensitivity outside the circle (see Fig. 2).

The optimal value  $Z_{ao}$  for maximizing the read range of a passive tag depends on this circle [see (12)], the impedance  $Z_{at}$  [see (3)] and  $Z_{ar}$  [see (8) and (9) for an approximation] can now be obtained with the following procedure:

If  $Z_{at}$  and  $Z_{ar}$  are both inside the circle, then the optimal impedance value can be obtained with:

$$Z_{ao} = \begin{cases} Z_{at} & \text{if } K \geq 1 \\ Z_{ar} & \text{if } K < 1 \end{cases} \quad (14)$$

Also, in this case maximum read range is bounded by the Friis equation if  $K \geq 1$  and by the Radar equation if  $K < 1$ .

If  $Z_{at}$  and  $Z_{ar}$  are both outside the circle, then the optimal impedance value can be obtained with:

$$Z_{ao} = \begin{cases} Z_{ar} & \text{if } K \geq 1 \\ Z_{at} & \text{if } K < 1 \end{cases} \quad (15)$$

Also, in this case maximum read range is bounded by the Radar equation if  $K \geq 1$  and by the Friis equation if  $K < 1$ .

If  $Z_{at}$  and  $Z_{ar}$  are inside and outside the circle, the problem can be defined as the maximization of (11) under the constraint  $d_t(Z_a) = d_r(Z_a)$ . Note that in this case, maximization of (11) under the previous constraint is equivalent to the maximization of either  $\tau_1$  [see (5)] or  $|\rho_1 - \rho_2|^2$  [see (6)]. The optimal

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

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**Require:**  $Z_{c1}, Z_{c2}, S_t, S_r, P_r$   
 Compute  $Z_{at}$  with (3)  
 Compute  $Z_{ar}$  by solving (7a) and (7b) [or with (8) and (9)]  
 Compute  $K$  with (12)  
 Compute  $R_o, X_o$  and  $r_o$  with (13)  
**if**  $Z_{at}$  and  $Z_{ar}$  are inside the circle **then**  
   **if**  $K \geq 1$  **then**  
      $Z_{ao} = Z_{at}$   
   **else**  
      $Z_{ao} = Z_{ar}$   
   **end if**  
**else if**  $Z_{at}$  and  $Z_{ar}$  are outside the circle **then**  
   **if**  $K \geq 1$  **then**  
      $Z_{ao} = Z_{ar}$   
   **else**  
      $Z_{ao} = Z_{at}$   
   **end if**  
**else**  
 Compute  $A, B$  and  $C$  with (19)  
 Compute  $\theta_o$  with (20)  
 Compute  $Z_{ao}$  with (21)  
**end if**

---

impedance value using (5) can be obtained by solving the following optimization problem:

$$Z_{ao} = \max_{R_a, X_a} \frac{4R_{c1}R_a}{(R_{c1} + R_a)^2 + (X_{c1} + X_a)^2} \quad (16)$$

$$\text{s.t.} \quad \begin{cases} \frac{(R_{c1} + R_a)^2 + (X_{c1} + X_a)^2}{(R_{c2} + R_a)^2 + (X_{c2} + X_a)^2} - K = 0 \\ R_a \geq 0 \end{cases}$$

Note that this optimization problem is strictly equivalent to the maximization of (6) under the same constraints. In this case, note that the read range is bounded by both the Friis equation and the Radar equation (which are equal). Open source solvers like IPOPT in CasADi [15] can be used to solve the optimization problem.

More interestingly, analytic solution can also be determined in this case by remarking that the first constraint of (16) can be parameterized by  $\theta$ :

$$\begin{cases} R_a = R_o + \cos \theta \\ X_a = X_o + \sin \theta \end{cases} \quad (17)$$

By re-injecting (17) inside the objective function of (16) and then differentiating with respect to  $\theta$ , extremums of the objective function can be determined by finding the roots of:

$$A \cos \theta + B \sin \theta = C \quad (18)$$

with  $A, B$  and  $C$  real numbers equal to:

$$\begin{cases} A = -2r_o R_o (X_o + X_{c1}) \\ B = -r_o [(R_o + R_{c1})^2 - r_o^2 - (X_o + X_{c1})^2] + 2R_o (R_{c1} + R_o) \\ C = 2r_o^2 (X_o + X_{c1}) \end{cases} \quad (19)$$

TABLE I  
UHF RFID CHIPS USED IN THE STUDY.

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

Note that (18) admits two solutions, noted  $\theta_{o1,2}$ , which correspond respectively to one maximum and one minimum and can be expressed as:

$$\theta_{o1,2} = \pm \arccos \left( \frac{C}{\sqrt{A^2 + B^2}} \right) + \arctan \left( \frac{B}{A} \right) \quad (20)$$

Note that a particular attention must be taken to the sign of  $A$  and  $B$  to estimate the correct angle. Finally, resistance and reactance of  $Z_{ao}$  can be expressed as:

$$\begin{cases} R_{ao} = R_o + r_o \cos(\theta_{o1,2}) \\ X_{ao} = X_o + r_o \sin(\theta_{o1,2}) \end{cases} \quad (21)$$

Note also that the constraint  $R_a > 0$  can simply be respected by discarding the solution based on the sign of  $R_{ao}$ .

The complete procedure is summarized in Algorithm 1. Octave/Matlab script for  $Z_{ao}$  estimation is also provided as free software [16]. Note that this procedure is general and allows one to maximize the read range of any passive tag as function of the two chip impedance states, the tag sensitivity and the reader parameters. Finally, the procedure is optimal whatever the reader and tag parameters which is not the case with the conjugate matching, which only covers a small subset of the optimal cases.

### III. RESULTS

Chips considered in this study are presented in Table I. The first chip is a low sensitivity chip, the second one is optimized to design semi-passive tags (battery assisted) and the last one is a high sensitivity chip. Note that chip sensitivity and chip impedance in the default state have been extracted directly from their respective datasheets. Chip impedance in the second state  $Z_{c2}$  is usually not given, however, chip architecture classically uses a FET transistor in parallel with the rectifier circuitry. Thus  $Z_{c2}$  can be obtained by considering that  $Z_{c1}$  is parallel with the resistance  $R_{mod}$  of the transistor [17]:

$$Z_{c2} = \frac{Z_{c1}R_{mod}}{Z_{c1} + R_{mod}} \quad (22)$$

The modulation resistance depends on the manufacturing process and can be in the range of [10; 100]  $\Omega$ . In the rest of this paper, we consider  $R_{mod} = 50 \Omega$  for all the chips. Note that measurements can be used to evaluate more accurately  $Z_{c2}$  for each chip.

For the reader side, we consider a reader of sensitivity  $S_r = -75$  dBm, a transmitted power of  $P_r = 30$  dBm and a gain  $G_r = 6$  dBi (in transmission and reception).

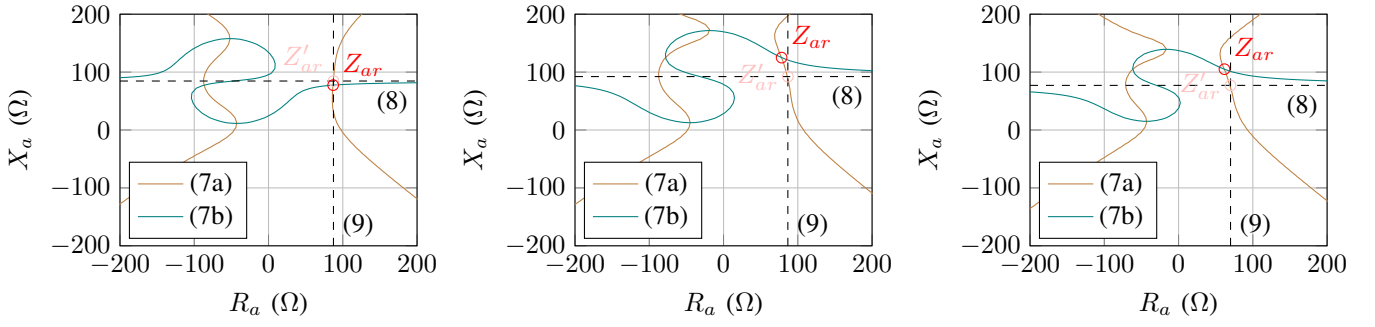


Fig. 3. Impedance matching maximizing the delta RCS for (a) Impinj Monza 2 chip, (b) Impinj Monza X-8K chip and (c) Impinj Monza R6-P chip.

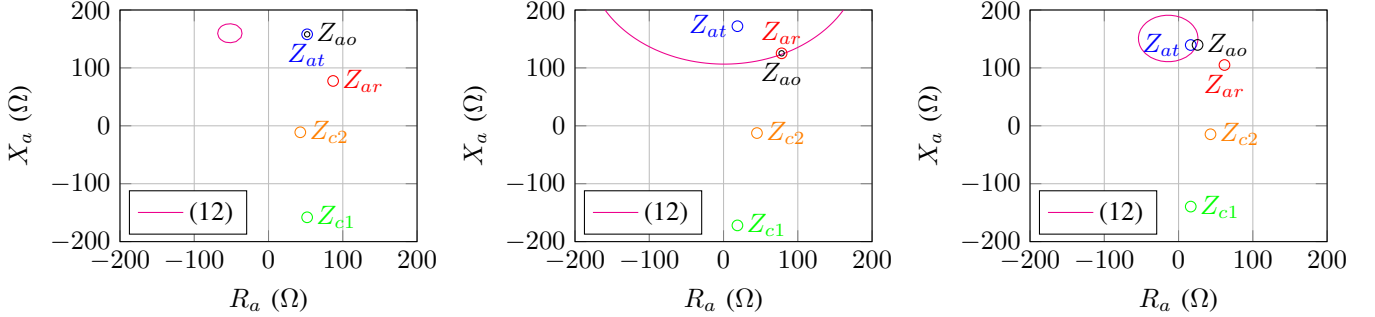


Fig. 4. Impedance matching maximizing the read range for (a) Impinj Monza 2 chip ( $K = 0.013$ ), (b) Impinj Monza X-8K chip ( $K = 0.39$ ) and (c) Impinj Monza R6-P chip ( $K = 0.083$ ).

### A. Differential Matching

As explained in Section II-B, maximization of the delta RCS as a function of the antenna impedance can be obtained by solving a system of two non-linear equations (7a) and (7b) (or by using (8) and (9) for an approximation). Fig. 3 presents the set of  $Z_a$  values satisfying (7a) and (7b) for the three different chips.  $Z_{ar}$  corresponds to the intersection between the blue curve and the red curve. For this impedance value, the delta RCS of the tag is maximum. Note that this maximum does not correspond to the maximization of the received power by the tag (which is obtained with the conjugate matching). Moreover, the approximation  $Z'_{ar}$  given by (8) and (9) also provides a good approximation of  $Z_{ar}$  when the discriminant of (7b) is significantly lower than zero.

Delta RCS values obtained using  $Z_{ar}$  is equal to  $68.7 \text{ cm}^2$ ,  $114 \text{ cm}^2$  and  $102 \text{ cm}^2$  for the Monza 2, Monza X-8K Dura and the Monza R6-P respectively. For comparison purposes, using classical conjugate matching  $Z_{at}$  corresponds to a delta RCS of  $40.7 \text{ cm}^2$ ,  $50.9 \text{ cm}^2$  and  $49.0 \text{ cm}^2$  for the same chips. Thus, in average,  $Z_{ar}$  allows one to increase the delta RCS by a factor 2 compared to classical conjugate matching.

### B. Optimal Matching

As explained in Section II-C, maximization of the read range can be obtained by choosing the antenna impedance to achieve the optimal trade-off between the power received by the tag and modulated power received by the reader. Fig. 4 presents the optimal value of  $Z_{ao}$  in order to maximize the read

range. This impedance value depends on  $Z_{at}$ ,  $Z_{ar}$  and their respective positions compared to the circle described by (12).

The Monza 2 chip has a high activation power, we can see that  $Z_{at}$  and  $Z_{ar}$  are both outside the circle. Optimal impedance matching corresponds in this case to the complex conjugate matching. The Monza X-8K Dura chip which is used in semi-passive tags, is characterized by a large circle which encompass  $Z_{at}$  and  $Z_{ar}$ . Optimal impedance matching corresponds in this case to the maximization of the modulated power by the tag. The Monza R6-P chip is passive chip with a high sensitivity, we can see that  $Z_{at}$  and  $Z_{ar}$  are inside and outside the circle respectively. Optimal impedance matching can not be achieved by  $Z_{at}$  or  $Z_{ar}$  but can be determined using the optimization under constraint using (16), and represents the optimal trade-off between the mismatch  $\tau_1$  and the modulated power  $\sigma_d$ . Note that the position of  $Z_{ao}$  does not lie on the line defined by  $Z_{at}$  and  $Z_{ar}$ .

Read range values obtained using  $Z_{ao}$  is equal to  $7.9 \text{ m}$ ,  $23.6 \text{ m}$  and  $20.6 \text{ m}$  for the Monza 2, Monza X-8K Dura and the Monza R6-P, respectively. Compared to classical conjugate matching, the read range can be increased by 22% for a Monza X-8K Dura chip. For the Monza R6-P chip, matching with  $Z_{ao}$  provides an improvement of 8%. Note that in both cases, the improvement can be done simply by carefully (re)designing the antenna. Thus the proposed method provides an easy way to increase the performance of a tag compared to classical conjugate matching used in the literature but depends on both tag and reader parameters.

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

MONZA 2						
	$Z_a$ ( $\Omega$ )	$\tau_1$	$\sigma_d$ ( $\text{cm}^2$ )	$d_t$ (m)	$d_r$ (m)	$d$ (m)
$Z_{at}$	$52 + j158$	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						
	$Z_a$ ( $\Omega$ )	$\tau_1$	$\sigma_d$ ( $\text{cm}^2$ )	$d_t$ (m)	$d_r$ (m)	$d$ (m)
$Z_{at}$	$17.8 + j172$	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						
	$Z_a$ ( $\Omega$ )	$\tau_1$	$\sigma_d$ ( $\text{cm}^2$ )	$d_t$ (m)	$d_r$ (m)	$d$ (m)
$Z_{at}$	$16.4 + j139.5$	1	49.0	21.1	19.1	19.1
$Z_{ar}$	$61.8 + j105$	0.56	102	15.7	23.0	15.7
$Z_{ao}$	$24.8 + j140$	0.96	66.9	20.6	20.6	20.6

### C. Performance comparison

Finally, the impact of each matching over the performance has been evaluated for the considered chips. All the results are summarized in Table II using the equations provided in Section II *i.e.*,  $\tau_1$ ,  $\sigma_d$ ,  $d_t$ ,  $d_r$  and  $d$  are computed with (5), (6), (4), (10) and (11), respectively. Optimal matching can be used to maximize the read range for all presented chips. We can also clearly see for the Monza R6-P that the maximization the read range can not be achieved by the conjugate matching neither by the differential matching. Optimal matching provides the optimal trade-off between the received power and the backscattered modulated power to maximize the read range. This optimal matching allows one to increase the read range of any tag based on the Monza R6-P chip by 8% simply by designing an antenna with an impedance of  $Z_{ao} = 24.8 + j140 \Omega$  (instead of the complex conjugate matching).

## IV. CONCLUSION

This paper shows that the classical complex conjugate matching used in UHF RFID is, in some cases, not optimal to maximize the performance. As contributions, we present two procedures to maximize the delta RCS and the read range of any tag. The first procedure allows to maximize the delta RCS of a tag and maximize the read range of semi-passive tags. The second one provides the exact solution to obtain the optimal impedance of the antenna in order to maximize the read range of any tag. This procedure depends on the states of the tag and its sensitivity but also on the transmitted power and reader power and sensitivity. Moreover, this approach can be described using simple geometrical concept. The paper shows that the read range associated a tag based on a Monza R6-P chip (respectively Monza X Dura) can increased by 8%

(respectively 22%) compared to classical conjugate matching. This technique allows one to increase the read range of any UHF semi-passive and passive tag simply (re)designing the antenna.

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