Backscattering Improvement of UHF RFID Tag Efficiency

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ABSTRACT: In this work, a tag-load selection methodology is proposed for optimized tag-to-reader backscatter communication. Derivation of the method is based on antenna/communication theory and applies to any tag-antenna, including minimum scattering antennas as a special case. In contrast to what is commonly believed, it is shown that amplitude maximization of complex reflection coefficient difference between the two states is not a sufficient condition for optimized tag's design. Maximization of backscatter carrier power per bit must be sought as well. Optimum load-selection for passive and semi-passive tags is linked to the tag-antenna's structural mode. A method that allows for the closed-form calculation of this parameter is put forward.

INTRODUCTION

Numerous applications of RF/RFID systems have emerged in diverse fields, like aerospace, healthcare, logistics, supply chain management, and defense [1]. A tag modulates the signal transmitted by the reader, by connecting alternatively to two different loads, as demonstrated in Fig. 1. In our work, it is shown that:

- For optimizing the backscatter communication; except of the amplitude reflection coefficient difference, tag antenna structural mode must be considered.
- For the radar cross section (RCS) derivation of the tag antenna, a closed-form expression of the appropriate structural mode is needed and will be given.

The proposed tag-load selection applies to *any* tag antenna, including minimum scattering antennas as a special case, and covers both passive as well as semi-passive tags.

CONNECTION TO PRIOR ART

The RCS of the tag's antenna depends on the connected load. Let $\vec{E}_i$ denote the complex backscattered field from the tag connected to a load Z_i (i=1 for bit '0' or i=2 for bit '1'). The tag's RCS σ_i in the two states is then given as, [2]:

$$\sigma_i \overset{\Delta}{=} \lim_{r\to+\infty} 4\pi r^2 \frac{|\vec{E}_i|^2}{|\vec{E}_{\text{ind}}|^2} = \frac{\lambda^2}{4\pi} G^2 |\Gamma_i - A_s|^2, \tag{1}$$

A_s corresponds to the structural mode of the antenna, G is the antenna's gain, λ the wavelength, $\vec{E}_{\text{ind}}$ the induced field at the tag, and Γ_i is the load-dependent reflection coefficient of the tag antenna-load system given by:

$$\Gamma_i \overset{\Delta}{=} \frac{Z_i - Z_a^*}{Z_i + Z_a} \tag{2}$$

Z_a is that tag antenna's impedance.

The authors in [3] exploited the Thevenin equivalent circuit of an antenna, carefully noting that such modeling assumes minimum scattering antennas. In such a case, [3]-[4], RCS equals to:

$$\sigma_i^{\text{thev}} = \frac{\lambda^2 G^2 R_a^2}{\pi |Z_i + Z_a|^2}, \tag{3}$$

Then, [3], they denote differential backscattered power as $P_{\text{diff.bs}} = 1/2\, |I_1 - I_2|^2\, R_a G$, where I_i is the current flowing at the Thevenin circuit corresponding to the two loads Z_i and define differential RCS $\Delta\sigma = P_{diff.bs}/S$, where S is the induced power density (in W/m^2) at the tag location from the field transmitted by the reader. Finally, they show that:

$$\Delta\sigma = \frac{\lambda^2 G^2}{4\pi} | \Gamma_1 - \Gamma_2 |^2 \quad (4)$$

Therefore, the system designer should maximize $| \Gamma_1 - \Gamma_2 |$, when the tag is connected to a minimum scattering antenna. $1/2 | I |^2 R_a G$ is a valid representation of the backscattered power from a tag, only for minimum scattering antennas. For example, for an open circuit load, thus Z_i=∞, by substituting in (3), the back-scattered RCS, based on the Thevenin equivalent circuit, is $\sigma_i^{\text{thev}} = 0$. On the contrary, by substituting in (1), which models the general tag-antenna case, $\sigma(Z_i = \infty) = (\lambda^2 / 4\pi) G^2 | 1 - A_s |^2 \neq 0$. The latter equals 0 only when A_s=1. As shown in [5], the antenna structural mode is generally different than unity.

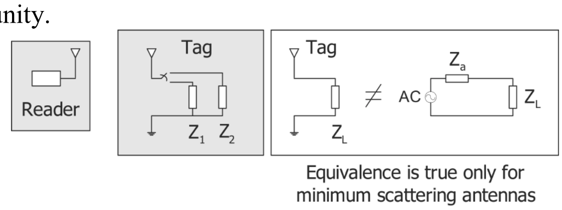

Fig. 1 Thevenin equivalent circuit for tag antennas.

TAG EFFICIENCY CONSTRAINTS

The scattered field $\vec{E}_i$ at location (r, θ, φ) when tag antenna is loaded with Z_i can be expressed as [6], [7]:

$$\vec{E}_i \equiv \vec{E}_i(r,\theta,\varphi) = \underbrace{I_{ind} \frac{\vec{E}_a(r,\theta,\varphi)}{I_a}}_{\vec{E}_0} (A_s - \Gamma_i) = \vec{E}_0(r,\theta,\varphi)(A_s - \Gamma_i) = \vec{E}_0 (A_s - \Gamma_i) \quad (5)$$

I_{ind} is the induced current by the incoming field at the tag antenna terminals, when the tag is terminated at load Z_a^*. $\vec{E}_a$ is the field radiated by the tag antenna at location (r, θ, φ), when the current at the tag antenna terminals is I_a and no external incident wave is applied to the tag antenna. The term $\vec{E}_0$ is independent of the tag load Z_i. By definition, the power P_i of the backscattered field for the two terminating loads Z_i (i=1,2) is given as:

$$P_i = (1/2\eta) | \vec{E}_i |^2 = S\,\sigma_i \quad (6)$$

From (6), it must be pointed out that the backscattered signal from the same tag and the same propagation conditions is not constant but depends on the tag's load, that is selected based on the tag bit information ($S\sigma_1$ for bit '0' or $S\sigma_2$ for bit '1'). Therefore, from (5), backscattered power depends on the complex reflection coefficient Γ_i, which is shaped by the tag's load as given in (2).

A. Constraint 1. Maximize Backscattered Carrier Power per Bit.

System designers should select loads Z_i, so that the average backscattered carrier power per bit $(P_1 + P_2)/2$ is maximized, or equivalently, by replacing in (6):

$$\max\{\sigma_1 + \sigma_2\} \quad (7)$$

In (1) it was shown that σ_i depends both on the load as well as on the load-independent antenna's structural mode A_s. So, it is important to derive the structural mode.

B. Constraint 2. Minimize Bit-Error-Rate Probability (BER) at the Reader

The tag designer should also select terminating loads Z_i at the tag, such that BER at the reader is minimized. The signal y_i received at the reader antenna is directly proportional to the backscattered field $\vec{E}_i$, given by (5), plus the additive receiver thermal noise:

$$y_i = \underbrace{a\vec{E}_i}_{x_i} + n, \quad (8)$$

a accounts for the transform of a field quantity (e.g. in V/m) to a signal quantity (e.g. in V). It is further assumed that thermal noise n is a complex, zero-mean, circularly symmetric Gaussian random variable with expected power $E\{|n|^2\} = N_0$. Assuming knowledge of a, maximum likelihood (ML) detection of $x_1 = a\vec{E}_1$ for bit '0' or $x_2 = a\vec{E}_2$ for bit '1', in the presence of zero-mean, additive complex circularly symmetric gaussian noise, amounts to selecting bit '0' when the received signal y is closer to x_1 ($|\mathrm{y}-\mathrm{x}_1|<|\mathrm{y}-\mathrm{x}_2|$), or bit '1' when the received signal is closer to x_2 ($|\mathrm{y}-\mathrm{x}_1|>|\mathrm{y}-\mathrm{x}_2|$). In other words, detection error *e* is performed when the amount of noise exceeds half the distance between x_1 and x_2. The probability of such event can be directly computed (e.g. see appendix in [8]), providing an expression of the BER at the reader

$$\Pr\{e\}\overset{\Delta}{=}Q\left(\frac{|\mathrm{x}_1-\mathrm{x}_2|}{2\sqrt{N_0/2}}\right)=Q\left(|a\vec{E}_0|\frac{|A_s-\Gamma_1-A_s+\Gamma_2|}{2\sqrt{N_0/2}}\right)=Q\left(|a\vec{E}_0|\frac{|\Gamma_1-\Gamma_2|}{2\sqrt{N_0/2}}\right), \tag{9}$$

where $Q(x)=(1/\sqrt{2\pi})\int_x^{+\infty}\exp\left(-x^2/2\right)dx$ is the Q-function [9], which decreases with increasing *x*. Therefore, BER minimization requires maximization of the reflection coefficient difference amplitude:

$$\max\{|\Gamma_1-\Gamma_2|\} \tag{9}$$

Notice that the above derivation has employed simple detection theory, without any type of Thevenin-based tag antenna-tag chip modeling or any prior assumption regarding the tag antenna or the tag circuitry. Also, it applies to any binary modulation. The result of (9) agrees with [3], where Thevenin equivalent circuit and minimum scattering antennas were considered. Moreover, from (9), maximization of the load-independent antenna-specific term $|\vec{E}_0|$ is also needed.

CLOSED-FORM CALCULATION OF TAG ANTENNA STRUCTURAL MODE

In order to calculate the structural mode parameter A_s, three values σ_1, σ_2, σ_3 of the antenna RCS are needed, corresponding to three different loads Z_1, Z_2, Z_3 (or equivalently reflection coefficients Γ_1, Γ_2, Γ_3). Antenna RCS can be measured experimentally [5] or estimated through simulation. Denote complex $\Gamma_i = x_i + jy_i$ that corresponds to load Z_i and RCS σ_i, with $i\in\{1,2,3\}$ and the unknown $A_s = x + jy$. From (1), we have three circle equations (**c₁**, **c₂**, **c₃**):

$$(x-x_1)^2+(y-y_1)^2=\frac{4\pi}{\lambda^2G^2}\sigma_1,\ (\mathbf{c}_1),\ (x-x_2)^2+(y-y_2)^2=\frac{4\pi}{\lambda^2G^2}\sigma_2,\ (\mathbf{c}_2),\ (x-x_3)^2+(y-y_3)^2=\frac{4\pi}{\lambda^2G^2}\sigma_3,\ (\mathbf{c}_3) \tag{10}$$

Dividing ($\mathbf{c}_1$) with ($\mathbf{c}_2$) and setting $k_{12}=\sigma_1/\sigma_2$, we get a new circle centered at (x_1^*, y_1^*), with radius r_1:

$$\begin{aligned}&(x-x_1^*)^2+(y-y_1^*)^2=r_1^2,\\&(x_1^*,y_1^*)=\left(\frac{x_1-\kappa_{12}\,x_2}{1-\kappa_{12}},\frac{y_1-\kappa_{12}\,y_2}{1-\kappa_{12}}\right),\ r_1^2=\left(\frac{x_1-\kappa_{12}\,x_2}{1-\kappa_{12}}\right)^2+\left(\frac{y_1-\kappa_{12}\,y_2}{1-\kappa_{12}}\right)^2+\frac{\kappa_{12}\,(x_2^2+y_2^2)}{1-\kappa_{12}}-\frac{x_1^2+y_1^2}{1-\kappa_{12}}\end{aligned} \tag{11}$$

Similarly, by dividing ($\mathbf{c}_1$) with ($\mathbf{c}_3$) and setting $k_{13}=\sigma_1/\sigma_3$, we get a circle centered at (x_2^*, y_2^*), with radius r_2

$$\begin{aligned}&(x-x_2^*)^2+(y-y_2^*)^2=r_2^2,\\&(x_2^*,y_2^*)=\left(\frac{x_1-\kappa_{13}\,x_3}{1-\kappa_{13}},\frac{y_1-\kappa_{13}\,y_3}{1-\kappa_{13}}\right),\ r_2^2=\left(\frac{x_1-\kappa_{13}\,x_3}{1-\kappa_{13}}\right)^2+\left(\frac{y_1-\kappa_{13}\,y_3}{1-\kappa_{13}}\right)^2+\frac{\kappa_{13}\,(x_3^2+y_3^2)}{1-\kappa_{13}}-\frac{x_1^2+y_1^2}{1-\kappa_{13}}\end{aligned} \tag{12}$$

Finally, dividing ($\mathbf{c}_2$) with ($\mathbf{c}_3$) and setting $k_{23}=\sigma_2/\sigma_3$, we get a circle centered at (x_3^*, y_3^*), with radius r_3

$$\begin{aligned}&(x-x_3^*)^2+(y-y_3^*)^2=r_3^2,\\&(x_3^*,y_3^*)=\left(\frac{x_2-\kappa_{23}\,x_3}{1-\kappa_{23}},\frac{y_2-\kappa_{23}\,y_3}{1-\kappa_{23}}\right),\ r_3^2=\left(\frac{x_2-\kappa_{23}\,x_3}{1-\kappa_{23}}\right)^2+\left(\frac{y_2-\kappa_{23}\,y_3}{1-\kappa_{23}}\right)^2+\frac{\kappa_{23}\,(x_3^2+y_3^2)}{1-\kappa_{23}}-\frac{x_2^2+y_2^2}{1-\kappa_{23}}\end{aligned} \tag{13}$$

The intersection of circles (11) and (12) gives:

$$\begin{aligned}&(x,y)=\left(x_1^*+\frac{a}{d}(x_2^*-x_1^*)\pm\frac{h}{d}(y_2^*-y_1^*),\,y_1^*+\frac{a}{d}(y_2^*-y_1^*)\mp\frac{h}{d}(x_2^*-x_1^*)\right),\\&\text{where } d=\sqrt{(x_1^*-x_2^*)^2+(y_1^*-y_2^*)^2},\ a=\frac{r_1^2-r_2^2+d^2}{2\,d},\ h=\sqrt{r_1^2-a^2}\end{aligned} \tag{14}$$

The pair (*x*,*y*) above that validates (13) provides the unknown $A_s=x+jy$. As an example, consider the case of $Z_a=6.7+148.8j$, $\Gamma_1=1$ (open circuit) with $\sigma_1=0.0098m^2$, $\Gamma_2=0$ (matched load) with $\sigma_2=0.0148m^2$ and $\Gamma_3=j$ (reactive load) with $\sigma_3=0.0146m^2$ [5]. The result of the above calculation provides exact value of $A_s=0.6047+0.5042j$, which is close to the approximate value provided in [5], where A_s is graphically estimated on a Smith chart.

EFFICIENT TAGS: CASE STUDY - DISCUSSION

In the next paragraphs, the proposed methodology is applied in the design of a passive and a semi-passive tag. Loads are selected, with respect to the tag-antenna's structural mode, for optimized backscatter communication.

A. Case I: Passive Tags

For battery-less passive tags, tag load Z_1 usually corresponds to perfect match (Γ_1=0). In that way, power transfer from tag antenna to tag chip is maintained, at least for the duration of bit '0'. The tag load Z_2 (and corresponding Γ_2) is selected such that Γ_2-A_s is collinear with Γ_1-A_s. Two possible solutions for Γ_2 on the unit circle are depicted: solution I and II (Fig. 2-left). Both satisfy constraint 2 given in (9), while solution II provides for higher average backscatter carrier power per bit (constraint 1) than solution I, since $|\Gamma_2 - A_s|$ is maximized. For the special case of A_s=1, one solution could be Γ_2=A_s=1. A better solution with higher backscattered carrier power per bit would be Γ_2=-1.

B. Case II: Semi-Passive Tags

Given that power transfer from reader (or tag antenna) to the tag chip is not needed during tag-to-reader communication, Γ_1 need not be equal to zero, while both reflection coefficients should be on the unit circle (in order to maximize $|\Gamma_1 - \Gamma_2|$). Fig. 2-right depicts two solutions that both achieve the maximum $|\Gamma_1 - \Gamma_2| = 2$. In general, solution II could represent any two diametrically opposite points on the unit circle. Both Solutions I and II in Fig. 2-right, as well as any two diametrically opposite points on the unit circle achieve the same σ_1+σ_2 (constraint 1 of (7)). The proof follows: denote Γ_1=a+jb, diametrically opposite Γ_2=-a-jb, both on the unit circle $|a|^2 + |b|^2 = 1$ and A_s=x+jy:

$$\sigma_1 + \sigma_2 \propto |\Gamma_1 - A_s|^2 + |\Gamma_2 - A_s|^2 = |(a-x) + j(b-y)|^2 + |-(a+x) - j(b+y)|^2 = 2 + 2|A_s|^2 \quad (15)$$

In other words, any diametrically opposite (Γ_1, Γ_2) on the unit circle satisfy both constraints. However, by selecting Γ_i on the line segment that is vertical to OA_s (Fig. 2-right) and crosses O, back-scattered power given by (5), (6) is equal for the two loads, achieving zero-tag efficiency variance.

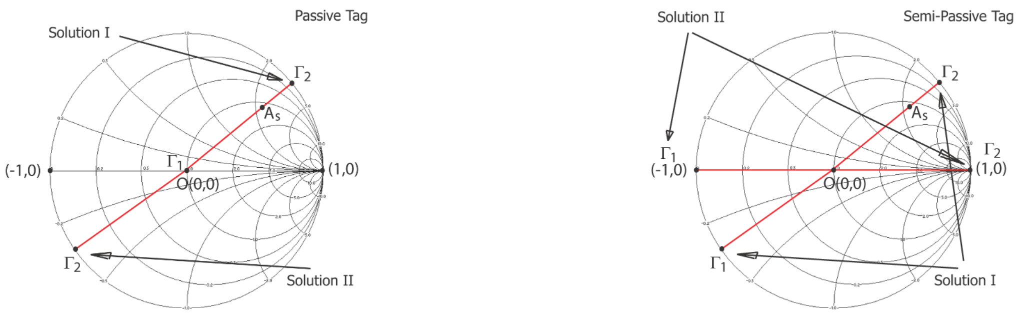

Fig. 2 Tag load selection and corresponding reflection coefficients Γ_i for a passive and a semi-passive tag.

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