Improving Backscatter Radio Tag Efficiency

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***Abstract*—This paper studies tag properties for optimized tag-to-reader backscatter communication. The latter is exploited in RF identification (RFID) systems and utilizes binary reflection coefficient change of the tag antenna-load circuit. It is shown that amplitude maximization of complex reflection coefficient difference between the two states is *not sufficient* for optimized tag-to-reader backscatter communication, contrary to what is commonly believed in the field. We provide a general tag load selection methodology that applies to any tag antenna, including minimum scattering antennas as a special case. The method is based on tag antenna structural mode closed-form calculation (given three values of tag radar cross section), employs simple antenna/communication theory, and applies to both passive, as well as semipassive RFID tags.**

***Index Terms*—Minimum scattering, receiver sensitivity, RF identification (RFID), structural mode.**

I. Introduction

IMPRESSIVE progress has been observed since the first efforts on backscatter radio [1]. Numerous and diverse applications have emerged, spanning RF identifications (RFIDs) in electronic supply chain to electronic music instrumentation [2] or software-defined implementations for ultra-low-cost and ultra-low-power environmental sensor networks [3]–[5].

We focus on the tag-to-reader link and study the properties of the RFID tag for optimized tag-to-reader communication. Backscatter radio binary-modulates information with reflection coefficient change, when the tag antenna is alternatively connected between two different loads (Fig. 1). Work and results apply to passive, as well as semipassive (battery-assisted) RFID tags.

The specific contributions are summarized as follows.

- Necessary conditions (*constraints*) for improved tag-to-reader backscatter communication are derived, while not restricting discussion to minimum scattering antennas or specific tag circuitry. It is shown that maximization of amplitude reflection coefficient difference is not sufficient; tag antenna structural mode should also be considered.

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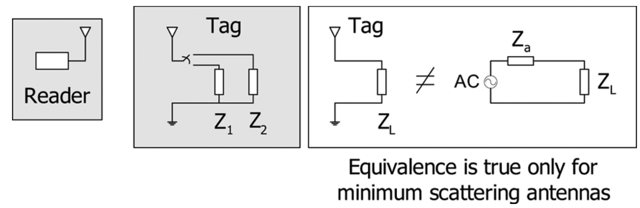


Fig. 1. Thevenin equivalent tag antenna-load circuit for the two terminating loads-states. Thevenin equivalent circuit is only valid for minimum scattering tag antennas. This work assumes no Thevenin modeling and studies the tag load selection problem for *any* tag antenna.

- Simple closed-form calculation of the tag antenna structural mode is provided. Proposed tag load selection for improved backscatter communication is based on the estimation of the tag antenna structural mode, applies to *any* tag antenna (including minimum scattering as special case), and covers both passive, as well as semipassive, tags.

Section II provides in more detail the connection of this work to prior art. Section III describes the constraints that the tag designer should adopt, utilizing communication theory, as well as the tag antenna structural mode. A method to calculate the tag antenna structural mode in closed form is provided in the Appendix . Section IV provides load selection design examples for both passive and semipassive tags. Finally, a conclusion is provided in Section V.

II. Connection to Prior Art

The ratio of power P_{out} *backscattered* from tag to reader and power P_{ind} *induced* at the tag defines the tag efficiency K (e.g., [6, eq. (6)])

$$G\,K \triangleq \frac{P_{\text{out}}}{P_{\text{ind}}} = \frac{S\,\sigma}{S\,A_{\text{eff}}} \Rightarrow \tag{1}$$

$$\sigma = G\,K\,A_{\text{eff}} = \frac{\lambda^2\,G^2}{4\pi}\,K \tag{2}$$

where A_{eff}, G is the tag antenna effective area and gain, respectively, λ is the carrier wavelength, S is the induced power density (in W/m^2) at the tag location from the field transmitted by the reader, and σ is the tag antenna radar cross section (RCS).

RCS depends on the load connected to the tag antenna. Assume that Z_1 is the load connected to the tag antenna when the tag information bit is "0" and Z_2 is the load when the tag information bit is "1" (Fig. 1). Also denote $\vec{E}_i$ the (complex) backscattered field from the tag antenna when the latter is terminated at Z_i ($i = 1$ for bit "0" or $i = 2$ for bit "1"). Consecutively, RCS σ_i is given [7], [8] by

$$\sigma_i \triangleq \lim_{r \longrightarrow +\infty} 4\pi r^2 \frac{|\vec{E}_i|^2}{|\vec{E}_{\text{ind}}|^2} = \frac{\lambda^2}{4\pi}\,G^2\,|\Gamma_i - A_s|^2 \tag{3}$$

where σ_i corresponds to tag load Z_i ($i = 1$ or $i = 2$), Z_a is the tag antenna impedance, and A_s corresponds to the *structural mode* of the tag antenna, which is a load-independent antenna quantity [8]. Its value is complex, in general, and depends on the geometry and materials used for the antenna construction. Furthermore,

$$\Gamma_i \triangleq \frac{Z_i - Z_a^*}{Z_i + Z_a} \tag{4}$$

is the (load dependent) reflection coefficient of the tag antenna–load system and

$$S = \frac{1}{2\eta}\,|\vec{E}_{\text{ind}}|^2 \tag{5}$$

assuming no polarization mismatch; η denotes the impedance of the propagation medium (120π in free space).

Nikitin *et al.* [9] exploited the Thevenin equivalent circuit of an antenna, carefully noting that such modeling assumes *minimum scattering* antennas. It can be easily shown that Thevenin equivalent circuit provides RCS equal to [6], [9]

$$\sigma_i^{\text{thev}} = \frac{\lambda^2 G^2 R_a^2}{\pi\,|Z_i + Z_a|^2} \tag{6}$$

or, equivalently from (2),

$$K_i^{\text{thev}} = \frac{4R_a^2}{|Z_i + Z_a|^2}. \tag{7}$$

The authors in [9] 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 when the antenna is connected to load Z_i ($i \in \{1,\ 2\}$) and show that

$$P_{\text{diff.bs}} = S\,\frac{\lambda^2 G^2}{4\pi}\,|\Gamma_1 - \Gamma_2|^2. \tag{8}$$

The ratio $P_{\text{diff.bs}}/S$ is coined in [9] as *differential RCS* $\Delta\sigma$. Thus, the system designer should maximize $|\Gamma_1 - \Gamma_2|$, when the tag is connected to a minimum scattering antenna. This work studies what is needed to be maximized (or minimized) for efficient tag-to-reader communication, employing detection theory and no Thevenin modeling (and thus, applies to *any* tag antenna, including minimum scattering antennas as a special case); $1/2|I|^2 R_a G$ is a valid representation of the backscattered power from tag to reader, only for minimum scattering antennas and not for the general tag antenna case: from Thevenin-produced equations (6) and (7), it can be seen that for open circuit load $Z_i = \infty$, the backscattered power from the tag is zero

$$K^{\text{thev}}(Z_i = \infty) = \sigma^{\text{thev}}(Z_i = \infty) = 0 \tag{9}$$

justifying the characterization *minimum scattering* antenna.

On the contrary, from (3), which applies to the general tag antenna case, it can be seen that RCS (and consecutively backscattered power from the tag to the reader) for the open circuit load is not zero

$$\sigma(Z_i = \infty) = \frac{\lambda^2}{4\pi}\,G^2\,|1 - A_s|^2 \neq 0. \tag{10}$$

The latter produces a zero power backscattered signal only for $A_s = 1$. The antenna structural mode A_s need not be unity, as shown in [10], where semipassive tags were studied, while A_s was estimated using graphical methods. In this study, we provide closed-form A_s calculation, while we study both passive, as well as semipassive, tags within more generalized context; our approach provides tag load selection constraints and rules without restricting discussion to specific tag/reader circuitry or minimum scattering antennas [11].

III. Tag Efficiency Constraints

From antenna scattering theory [8], [12], it is known that the scattered field from the tag back to the reader is given by

$$\vec{E}_i = \vec{E}_{\text{str}} - \vec{E}_{\text{ant}}(Z_i, I_a). \tag{11}$$

The first term $\vec{E}_{\text{str}}$ corresponds to the load-independent tag antenna *structural* mode. The second term $\vec{E}_{\text{ant}}$ denotes the *antenna* mode and depends on the connected (to the antenna) load Z_i, as well as the current I_a at the antenna terminals, at the absence of any external field. Specifically, the scattered field $\vec{E}_i$ at direction (r, θ, ϕ) when the tag antenna is loaded with Z_i can be expressed as [12], [13]

$$\vec{E}_i \equiv \vec{E}_i(r,\theta,\phi) = \underbrace{I_{\text{REF}}\,\frac{\vec{E}_a(r,\theta,\phi)}{I_a}}_{\vec{E}_0}\,(A_s - \Gamma_i) \tag{12}$$

$$= \vec{E}_0(r,\theta,\phi)\,(A_s - \Gamma_i) \equiv \vec{E}_0\,(A_s - \Gamma_i) \tag{13}$$

$$= \vec{E}_0\,\frac{2\sqrt{\pi}}{\lambda G}\sqrt{\sigma_i}\,e^{+j\phi_i} \tag{14}$$

where I_{REF} is the current induced by the incoming field at the tag antenna terminals, when the tag is terminated at load Z_a^*, and $\vec{E}_a$ is the field radiated by the tag antenna when the current at the tag antenna terminals is I_a and no external incident wave is applied to the tag antenna. In (14), ϕ_i denotes the phase of the complex parameter $A_s - \Gamma_i$, while the amplitude of $A_s - \Gamma_i$ is set according to (3).

Notice that the term $\vec{E}_a/I_a$ is independent of I_a and the term $\vec{E}_0$ is independent of the tag load Z_i. For example, assuming free-space propagation in a lossless medium, $\vec{E}_a(r,\theta,\phi)/I_a = -j\eta\;1/2\lambda r\;\vec{\ell}_e(\theta,\phi)\;e^{-j\beta r}$, where $\vec{\ell}_e$ is the effective length of the receiving antenna at (r,θ,ϕ) and $\beta = 2\pi/\lambda$. We will not necessarily assume free space in this study, but instead simply exploit the fact that $\vec{E}_0$ is tag load independent.

By definition, power P_i ($i = 1$ or $i = 2$) of the backscattered field for the two different terminating loads $\{Z_1,\ Z_2\}$ is given by

$$\frac{1}{2\eta}|\vec{E}_i|^2 \propto P_i = S\sigma_i \tag{15}$$

assuming no losses due to polarization mismatch between tag and reader antennas. Notice that the power of the backscattered signal is not, in general, constant, but instead depends on the tag bit information ($P_1 = S\sigma_1$ for information bit "0" and $P_2 = S\sigma_2$ for information bit "1" in Fig. 2). Therefore, backscattered

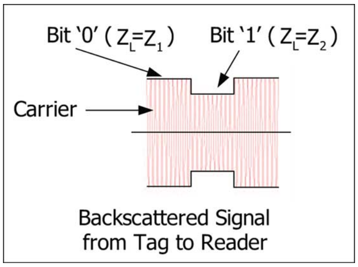


Fig. 2. Backscatter radio technique: signal backscattered from tag to reader binary-modulates information by changing the terminating tag load Z_L between two states; each state corresponds to bit "0" or "1."

signal power depends on the (in general, complex) reflection coefficient Γ_i (Γ_1 for bit "0" and Γ_2 for bit "1").

A. Maximum Backscattered Carrier Power Per Bit (Constraint 1)

System designer should select loads $Z_1,\ Z_2$ such that backscattered signal power is maximized, regardless of the transmitted tag bits. In other words, the system designer should maximize average backscattered carrier power per bit $(P_1+P_2)/2$, or equivalently, according to (15)

$$\max\{\sigma_1+\sigma_2\}. \tag{16}$$

This is a necessary condition that maximizes: 1) carrier signal, on top of which tag information will be modulated and 2) signal-to-noise ratio (SNR) at the reader's receiver that should exceed th e receiver's *sensitivity* for successful tag information extraction. In other words, neglecting the above constraint increases the chances for received power below reader's receiver sensitivity, and thus, no tag information reception. For semipassive tags, where in the forward link the received power is not exploited, but only decoded, the above constraint is important. Passive tags, which to date are forward-link limited, seem to be more lenient to the constraint [14]. However, the constraint will be valid, as the required power for their integrated circuits (ICs) is decreased with continued progress.

Notice that σ_i also depends on the load-independent structural mode parameter A_s of the tag antenna. Thus, the above maximization involves A_s. The Appendix provides a simple method for closed-form calculation of this parameter, for any tag antenna, given (measured or simulated) values of the tag's RCS.

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

Assuming that received signal power is above the receiver's sensitivity, the tag designer should also select terminating loads Z_i ($i=1$ or $i=2$) at the tag, such that BER at the reader is minimized. The signal y_i, received at the reader antenna at point (r,θ,ϕ), will be directly proportional to the backscattered field $\vec{E}_i$ at (r,θ,ϕ), given by (14), plus additive receiver thermal noise

$$y_i = h\underbrace{a\vec{E}_i}_{x_i}+n = hx_i+n \tag{17}$$

where the complex parameter h corresponds to the wireless channel (from tag to reader), a accounts for the transform of a field quantity (e.g., in V/m) to a signal quantity (e.g., in V), and finally, thermal noise n is assumed a complex zero-mean circularly symmetric Gaussian random variable with expected power $\mathbb{E}\left\{|n|^2\right\}=\mathcal{N}_0$. Notice that for a given point (r,θ,ϕ) at space, $a\vec{E}_i$ is a complex number.

The above flat fading model accounts for multipath, including both line-of-sight (LOS), as well as non-LOS tag-reader communication. No specific assumptions regarding the statistical distribution of h is needed in our study. For cases where the tag-to-reader channel coherence bandwidth is smaller than the bit-rate (frequency selective nonflat wireless channel), deterministic modeling tools could be employed (e.g., ray tracing), which is beyond the scope of this paper. It is further noted that link budget analysis for the backscatter radio channel have recently started to appear in the literature (e.g., see [15] and the references therein).

Assuming knowledge of a and h (coherent receiver), 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 hx_1 ($|y-hx_1|<|y-hx_2|$), or bit "1" when the received signal is closer to hx_2 ($|y-hx_1|>|y-hx_2|$). In other words, detection error e is performed when the amount of noise exceeds half the distance between hx_1 and hx_2. The probability of such an event can be directly computed (e.g., see Appendix A in [16]), providing an expression of the BER to the reader

$$\Pr\{e\} \triangleq Q\left(\frac{|hx_1-hx_2|}{2\sqrt{\frac{\mathcal{N}_0}{2}}}\right) \tag{18}$$

$$= Q\left(|h||a\vec{E}_0|\,\frac{|A_s-\Gamma_1-A_s+\Gamma_2|}{2\sqrt{\frac{\mathcal{N}_0}{2}}}\right) \tag{19}$$

$$= Q\left(|h||a\vec{E}_0|\,\frac{|\Gamma_1-\Gamma_2|}{2\sqrt{\frac{\mathcal{N}_0}{2}}}\right) \tag{20}$$

where $Q(x)=(1/\sqrt{2\pi})\int_x^{+\infty}\exp\left(-x^2/2\right)dx$ is the Q function [17], which decreases with increasing x.

Therefore, BER minimization requires maximization of the reflection coefficient difference amplitude

$$\max\{|\Gamma_1-\Gamma_2|\}. \tag{21}$$

The above derivation is based on the ML (minimum distance) detector and applies to *any* binary modulation. That remark is important since environmental conditions, such as electromagnetic (EM) coupling at the vicinity of the tag or the reader, could alter the transmitted signals. A similar result, involving received voltage and the complementary error function has been reported in [12] for the specific case of amplitude-shift keying (ASK) and phase-shift keying (PSK) modulation (used in EPC C1G2) and the receiver from [11] or nonideal binary modulation in [18]. The result of (21) agrees with [9], where Thevenin-equivalent circuit and minimum scattering antennas were assumed. Notice that the above derivation has employed simple detection theory, without any type of Thevenin-based antenna-tag chip modeling or any prior assumption regarding the tag antenna or the tag circuitry.

It is further noted that

$$\Pr\{e\} \triangleq Q\left(\frac{|hx_1 - hx_2|}{2\sqrt{\frac{\mathcal{N}_0}{2}}}\right) = Q\left(|h||a\vec{E}_0|\,\frac{|\Gamma_1-\Gamma_2|}{2\sqrt{\frac{\mathcal{N}_0}{2}}}\right) = Q\left(\frac{|h|\sqrt{|x_1|^2+|x_2|^2-2\mathrm{Real}\{x_1 x_2^*\}}}{2\sqrt{\frac{\mathcal{N}_0}{2}}}\right) \quad (22)$$

$$= Q\left(|h|\frac{\sqrt{\pi}}{\lambda G}|a\vec{E}_0|\frac{\sqrt{\sigma_1+\sigma_2-2\sqrt{\sigma_1}\sqrt{\sigma_2}\cos(\delta\phi)}}{\sqrt{\frac{\mathcal{N}_0}{2}}}\right) \quad (23)$$

where $\delta\phi = \phi_1 - \phi_2$ is the phase difference of the backscattered (from the tag) binary signals, according to (14) and definition of x_i in (17).

For PSK modulation, $\cos(\phi_1 - \phi_2) = -1$. Passive tags can have $|\Gamma_1|/|\Gamma_2| = \kappa \leq 1$ and $|\Gamma_1 - \Gamma_2| \leq 1+\kappa \leq 2$ (notice that for $\Gamma_2 = 1$ in this case, $|\Gamma_1 - \Gamma_2| = 1+\kappa$). Semipassive (battery assisted) tags can have $|\Gamma_1|/|\Gamma_2| = 1$ and $|\Gamma_1 - \Gamma_2| \leq 2$ with $|\Gamma_1 - \Gamma_2| = 2$ the preferred value.

Similarly, for ASK modulation, $\cos(\phi_1 - \phi_2) = +1$. For passive tags, $\Gamma_1 = 0$ and $|\Gamma_1 - \Gamma_2| \leq 1$. For semipassive tags and on–off keying (OOK), $\Gamma_1 = A_s$ ($\sigma_1 = 0$) and $|\Gamma_1 - \Gamma_2| = (1+\kappa)|\Gamma_2| \leq 1+\kappa$. Notice that, in this case of OOK, the value of Γ_2 that maximizes $|\Gamma_1 - \Gamma_2| = 1+\kappa$ should have amplitude $|\Gamma_2| = 1$ and phase difference π compared to phase of Γ_1. In other words, $\cos(\theta_1 - \theta_2) = -1 \neq \cos(\phi_1 - \phi_2)$, where θ_i is the phase of Γ_i. That means that the phase difference of reflection coefficients does not necessarily define the modulation type.

Furthermore, the above example shows that careful selection of the modulation and respective minimization of reader BER could employ estimation of the tag antenna structural mode A_s ($\Gamma_1 = A_s$ for the above OOK example), which is in sharp contrast to what is commonly believed in the field. The Appendix provides a method for A_s estimation for any tag antenna type.

Summarizing for a (nonideal) pseudo-PSK (or ASK) modulation (studied in [19]), the following inequality holds:

$$0 \leq |\Gamma_1 - \Gamma_2| \leq 1+\kappa \leq 2. \quad (24)$$

Finally, maximization of the load-independent antenna-specific term $|\vec{E}_0|$ is also needed for reduced BER. Additionally, maximization of $\sigma_1 + \sigma_2$ in (16) requires consideration of the antenna-specific structural mode parameter A_s, already discussed in Section III-A. Thus, maximization of $|\Gamma_1 - \Gamma_2|$, even though necessary, is clearly not sufficient for improved backscatter tag-to-reader communication.

C. Note on Tag Efficiency Variance

We have already noted that backscattered power is not, in general, constant, but instead depends on tag bit information. If backscattered field power P_{out} varies between P_1 and P_2, then tag efficiency K also varies for given induced reader field density S at the tag [according to (2) and (15)]

$$\mathsf{var}(K) = \frac{16\pi^2}{\lambda^4\, G^4\, S^2}\,\mathsf{var}(P_{\text{out}}) \propto \mathsf{var}(P_{\text{out}}) \quad (25)$$

where $\mathsf{var}(x)$ denotes the statistical variance of x.

For N consecutive backscattered bits from tag to reader, the average backscattered power is given (for large N according to the law of large numbers) by

$$P_{\text{out}}(N) = \frac{\mu P_1 + (N-\mu)P_2}{N} = \frac{P_1 - P_2}{N}\mu + P_2 \quad (26)$$

where μ is binomially distributed

$$\Pr\{\mu\} = \binom{N}{\mu}\left(\frac{1}{2}\right)^{\mu}\left(\frac{1}{2}\right)^{N-\mu} = \binom{N}{\mu}\left(\frac{1}{2}\right)^{N}. \quad (27)$$

Thus,

$$\mathsf{var}(P_{\text{out}}(N)) = \left(\frac{P_1 - P_2}{N}\right)^2 \mathsf{var}(\mu) \quad (28)$$

$$= \frac{(P_1 - P_2)^2}{4N} = \frac{S^2\,(\sigma_1 - \sigma_2)^2}{4N} \quad (29)$$

where we have used (15) and the fact that $\mathsf{var}(\mu) = N/4$, according to (27). Exploiting (29) in(25), we get

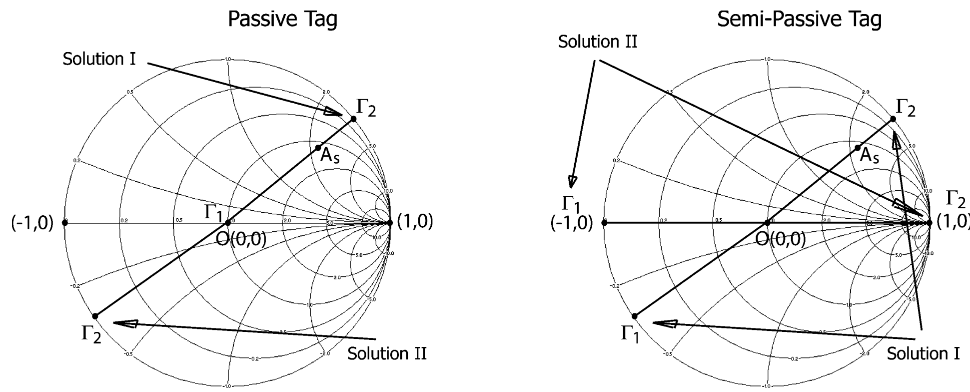
$$\mathsf{var}(K) = \frac{4\pi^2}{\lambda^4\, G^4}\frac{(\sigma_1 - \sigma_2)^2}{N} \propto \frac{(\sigma_1 - \sigma_2)^2}{N}. \quad (30)$$

For example, for the 911-MHz passive tag antenna proposed in [20] and $N = 96$, tag efficiency variance[1] amounts to $\mathsf{var}(K) = 0.0033 = (0.057)^2$. System engineers should take into account its standard deviation and worst case analysis should be performed. Future work should further study tag efficiency variance as a function of specific reader implementations and backscatter radio protocols.

IV. Efficient Tags: Case Study

Passive (battery-less) tags usually employ, apart from the tag antenna, digital logic in the form of a low power microcontroller or an application-specific IC. Such logic is designed to draw a

[1]EPC class 1 generation 2 (EPC Gen 2 for brevity) employs at least 96 bits for any tag-transmitted ID ($N \geq 96$). A Gen 2 standard is available online at http://www.epcglobalinc.org/standards/uhfc1g2



(a) (b)

Fig. 3. Selection of tag load and corresponding reflection coefficients Γ_1, Γ_2 for given tag antenna structural mode A_s. The depicted selections minimize reader detection probability, but provide different average backscattered carrier power per bit. Both passive and semipassive tags are considered (a) Passive tag. (b) Semipassive tag.

small amount of current (low power) and is usually modeled by a high resistance connected in parallel to a capacitive load (or equivalently, a small resistive load in series with a capacitive load) (e.g., [9] and [21]). A voltage multiplier and regulator is also needed to power the tag logic (chip), as well as the backscattered field modulator that changes the overall impedance, seen by the tag antenna, between two loads (Z_1 and Z_2 in Fig. 1). Given that the tag antenna has, in general, different equivalent impedance than the chip, a matching network between the antenna and chip is utilized.

This is the approach followed in this study for the case of passive tags. Depending on the selected load, the modulation can change the amplitude of the backscattered field (usually by changing the real part of the load and corresponding to ASK modulation) or the phase of the backscattered field (usually by changing the imaginary part of the load and corresponding to PSK modulation).

Alternatively, the passive-tag designer could trade the amount of power scattered back (to the reader) with power delivered to the tag chip, using imperfect matching (e.g., see discussion in [22] or in [14, Ch. 5]).

In the following, we provide general tag load selection rules for both passive, as well as semipassive tags, without restricting discussion to specific tag designs or minimum-scattering antennas only (we assume, in general, that $A_s \neq 1$).

A. Passive Tags

For batteryless passive tags, tag load Z_1 usually corresponds to perfect match ($\Gamma_1 = 0$). In that way, power transfer from the 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 $\Gamma_2 - A_s$ is collinear with $\Gamma_1 - A_s$. Two possible solutions for Γ_2 on the unit circle are depicted: solution I and II (Fig. 3, left). Both satisfy constraint 2 of (21), 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 $\Gamma_2 = A_s = 1$. A better solution with higher backscattered carrier power per bit would be $\Gamma_2 = -1$.

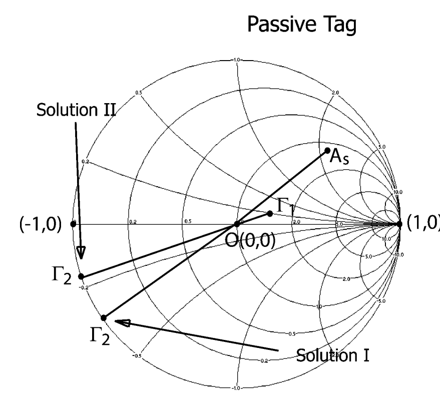


Fig. 4. Selection of tag load for the case of passive tag with imperfect matching ($\Gamma_1 \neq 0$). Depicted solutions I and II satisfy constraints 1 and 2, respectively.

An alternative approach (for the general case of $A_s \neq 1$) uses $\Gamma_2 = A_s$. In that way, tag efficiency variance proportional to $\sigma_1 - \sigma_2$ is slightly reduced at the expense of higher BER at the reader (since $|\Gamma_1 - \Gamma_2|$ is also reduced, compared to solution II depicted in Fig. 3, left).

Fig. 4 depicts the case where perfect matching for load Z_1 cannot be achieved, either due to parasitic elements on the printed circuit board and/or the fact that tags operate in a range of carrier frequencies (and not a single carrier frequency). The depicted reflection coefficient Γ_1 corresponds to a voltage standing-wave ratio (VSWR) on the order of 1.5:1. Depicted solution I for Γ_2 (and respective load Z_2) maximizes average backscattered carrier per bit (16) while achieving near-maximum $|\Gamma_1 - \Gamma_2|$; solution II maximizes $|\Gamma_1 - \Gamma_2|$ (21) while achieving near-maximum average backscattered carrier per bit. A system designer could select either solutions or a reflection coefficient (and respective load) on the unit circle and between the two aforementioned points.

In any case of matching (perfect or imperfect), it becomes clear that passive tag design for improved tag-to-reader backscatter communication requires consideration of parameter A_s, which is an antenna-specific load-independent parameter. Its calculation is provided in the Appendix.

A first example can be given for a planar tag, operating at 915 MHz with $Z_a = 6.7 + j148.8$. Given RCS values for different loads, the Appendix method calculates structural mode parameter $A_s = 0.6047 + j0.5042 = 0.7873 < 39.82°$. Solution I with $\Gamma_2 = 1 < 39.82°$ provides $\sigma_2^{\mathrm{I}} = 0.0011$ m^2. Solution II with $\Gamma_2 = 1 < (180 + 39.82)°$ achieves $\sigma_2^{\mathrm{II}} = 0.0763$ m^2. Thus, the ratio $(\sigma_2^{\mathrm{II}}+\sigma_1)/(\sigma_2^{\mathrm{I}}+\sigma_1) = 5.73$ with σ_1 the RCS for zero reflection coefficient $\Gamma_1 = 0$ (matched load). The observed ratio corresponds to gain of 7.58 dB in terms of received average carrier power per bit that could be effectively translated in an improved link budget. For example, when solution I provides a link budget that operates the reader $\sim$ 7 dB below its minimum received power (sensitivity) threshold, solution II can provide reception with the BER given by (20).

A second example contains the case of a passive tag antenna fabricated with a thin copper layer on PET ($\epsilon_r = 3.2$) at 911 MHz with $Z_a = 2 + j146$ and near-isotropic RCS [20]. For matched load ($\Gamma_1 = 0$), RCS amounts to $\sigma_1 = 0.0044$ m^2, and for $\Gamma = -1$, RCS amounts to 0.0141 m^2. Since from [20] only two different RCS values are provided, the structural mode was found to be $A_s = 0.0062 \pm j0.7114$, assuming uniform antenna gain ($G = 1$). Consecutively, $\Gamma_2^{\mathrm{I}} = 0.0868 \pm j0.9962$ with $\sigma_2^{\mathrm{I}} = 0.0007$ m^2 and $\Gamma_2^{\mathrm{II}} = -0.0868 \mp j0.9962$ with $\sigma_2^{\mathrm{II}} = 0.0254$ m^2. Thus, the ratio $(\sigma_2^{\mathrm{II}}+\sigma_1)/(\sigma_2^{\mathrm{I}}+\sigma_1) = 5.84$, resulting to a power gain of 7.66 dB, which effectively improves link budget.

B. Semipassive (Battery-Assisted) Tags

For semipassive tags, the available battery powers the tag chip during transmission of information from the tag to the reader. The battery is used to energize the tag chip and it is not used for any type of signal conditioning such as signal amplification, filtering, etc. Therefore, the mechanism for tag-to-reader communication is through backscattering, and hence, the term *semipassive*. Thus, semipassive tags do not require power scavenging and relevant voltage regulators.

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. 3, 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. 3, right, as well as any two diametrically opposite points on the unit circle achieve the same $\sigma_1 + \sigma_2$ [constraint 1 of (16)]. The proof follows: denote $\Gamma_1 = a + jb$, diametrically opposite $\Gamma_2 = -a - jb$, both on the unit circle $|a|^2 + |b|^2 = 1$ and $A_s = x + jy$

$$\sigma_1 + \sigma_2 \propto |\Gamma_1 - A_s|^2 + |\Gamma_2 - A_s|^2 \tag{31}$$
$$= |(a-x) + j(b-y)|^2 + |-(a+x) - j(b+y)|^2 \tag{32}$$
$$= 2 + 2\,|A_s|^2. \tag{33}$$

In other words, solutions I and II of Fig. 3, right, as well as any diametrically opposite (Γ_1, Γ_2) on the unit circle maximize $|\Gamma_1 - \Gamma_2|$ (constraint 2) and achieve the same sum in (16) (constraint 1). In order to maximize the sum of constraint 1, the tag antenna-specific parameter $|A_s|$ must be maximized, i.e., the tag antenna should be carefully designed.

For the special case of $A_s = 1$, one possible solution is given by $\Gamma_1 = A_s = 1,\ \Gamma_2 = -1$. From the above, it is seen that the solution $\Gamma_1 = j,\ \Gamma_2 = -j$ provides the same results in terms of constraints 1 and 2 (for $A_s = 1$), while achieving zero tag efficiency variance [see (30)].

An alternative approach (for the general case of $A_s \neq 1$) is to select $\Gamma_2 = A_s$ and Γ_1 on the unit circle, diametrically opposite to $\overrightarrow{OA_s}$. Such a selection clearly provides higher detection error probability (since $|\Gamma_1 - \Gamma_2|$ is reduced), while providing smaller tag efficiency variance (compared to solution I of Fig. 3, right).

V. Conclusion

Load-independent antenna parameters should be considered for improved tag-to-reader communication, contrary to what is commonly believed in the field. We provided simple rules on selecting the terminating loads for efficient tag-to-reader backscatter communication. Derivation employed basic communication theory without restricting discussion to minimum scattering antennas. It was shown that maximization of reflection coefficient difference amplitude $|\Gamma_1 - \Gamma_2|$ is not sufficient since additional constraints exist, while antennas are not necessarily minimum scattering (structural mode $A_s \neq 1$). A methodology was provided to select the tag loads for both passive, as well as semipassive, tags based on the tag antenna structural mode. A simple closed-form calculation of the structural mode for *any* tag antenna was also given.

Appendix
Closed-Form Calculation of Tag Antenna Structural Mode

In order to calculate the structural mode parameter A_s, three values $\sigma_1,\ \sigma_2,\ \sigma_3$ of the antenna RCS are needed, corresponding to three different loads $Z_1,\ Z_2,\ Z_3$ (or equivalently, reflection coefficients $\Gamma_1,\ \Gamma_2,\ \Gamma_3$). Antenna RCS can be measured experimentally [6] 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 (3), we have three circle equations

$$(x - x_1)^2 + (y - y_1)^2 = \frac{4\pi}{\lambda^2 G^2}\sigma_1 \tag{A.1}$$
$$(x - x_2)^2 + (y - y_2)^2 = \frac{4\pi}{\lambda^2 G^2}\sigma_2 \tag{A.2}$$
$$(x - x_3)^2 + (y - y_3)^2 = \frac{4\pi}{\lambda^2 G^2}\sigma_3. \tag{A.3}$$

Dividing (A.1) by (A.2) and setting $\kappa_{12} = \sigma_1/\sigma_2$, we get a circle equation centered at $(x_1^*,\ y_1^*)$ and radius r_1

$$(x_1^*,\ y_1^*) = \left(\frac{x_1 - \kappa_{12}\, x_2}{1 - \kappa_{12}},\ \frac{y_1 - \kappa_{12}\, y_2}{1 - \kappa_{12}}\right)$$
$$r_1^2 = \left(\frac{x_1 - \kappa_{12}\, x_2}{1 - \kappa_{12}}\right)^2 + \left(\frac{y_1 - \kappa_{12}\, y_2}{1 - \kappa_{12}}\right)^2 + \frac{\kappa_{12}\,(x_2^2 + y_2^2)}{1 - \kappa_{12}} - \frac{x_1^2 + y_1^2}{1 - \kappa_{12}},\ (x - x_1^*)^2 + (y - y_1^*)^2 = r_1^2. \tag{A.4}$$

Dividing (A.1) by (A.3) and setting $\kappa_{13} = \sigma_1/\sigma_3$, we get a circle equation centered at $(x_2^*,\ y_2^*)$ and radius r_2

$$\begin{aligned}(x_2^*,\ y_2^*) &= \left(\frac{x_1 - \kappa_{13}\, x_3}{1-\kappa_{13}},\ \frac{y_1 - \kappa_{13}\, y_3}{1-\kappa_{13}}\right)\\ r_2^2 &= \left(\frac{x_1 - \kappa_{13}\, x_3}{1-\kappa_{13}}\right)^2 + \left(\frac{y_1 - \kappa_{13}\, y_3}{1-\kappa_{13}}\right)^2\\ &\quad + \frac{\kappa_{13}\,(x_3^2+y_3^2)}{1-\kappa_{13}} - \frac{x_1^2+y_1^2}{1-\kappa_{13}}, (x-x_2^*)^2\\ &\quad + (y-y_2^*)^2\\ &= r_2^2. \end{aligned} \tag{A.5}$$

Finally, dividing (A.2) by (A.3) and setting $\kappa_{23} = \sigma_2/\sigma_3$, we get a circle equation centered at $(x_3^*,\ y_3^*)$ and radius r_3

$$\begin{aligned}(x_3^*,\ y_3^*) &= \left(\frac{x_2 - \kappa_{23}\, x_3}{1-\kappa_{23}},\ \frac{y_2 - \kappa_{23}\, y_3}{1-\kappa_{23}}\right)\\ r_3^2 &= \left(\frac{x_2 - \kappa_{23}\, x_3}{1-\kappa_{23}}\right)^2 + \left(\frac{y_2 - \kappa_{23}\, y_3}{1-\kappa_{23}}\right)^2\\ &\quad + \frac{\kappa_{23}\,(x_3^2+y_3^2)}{1-\kappa_{23}} - \frac{x_2^2+y_2^2}{1-\kappa_{23}}, (x-x_3^*)^2\\ &\quad + (y-y_3^*)^2\\ &= r_3^2. \end{aligned} \tag{A.6}$$

If a solution $(x,\ y)$ exists, that will be the intersection of circles of (A.4) and (A.5) that validates circle of (A.6)

$$\begin{aligned}(x,\ y) = \Bigg(& x_1^* + \frac{a}{d}\,(x_2^* - x_1^*) + \frac{h}{d}\,(y_2^* - y_1^*),\\ & y_1^* + \frac{a}{d}\,(y_2^* - y_1^*) - \frac{h}{d}\,(x_2^* - x_1^*)\Bigg) \end{aligned} \tag{A.7}$$

or

$$\begin{aligned}(x,\ y) = \Bigg(& x_1^* + \frac{a}{d}\,(x_2^* - x_1^*) - \frac{h}{d}\,(y_2^* - y_1^*),\\ & y_1^* + \frac{a}{d}\,(y_2^* - y_1^*) + \frac{h}{d}\,(x_2^* - x_1^*)\Bigg) \end{aligned} \tag{A.8}$$

where

$$d = \sqrt{(x_1^* - x_2^*)^2 + (y_1^* - y_2^*)^2} \tag{A.9}$$

$$a = \frac{r_1^2 - r_2^2 + d^2}{2d} \quad h = \sqrt{r_1^2 - a^2}. \tag{A.10}$$

The pair $(x,\ y)$ above that validates (A.6) provides the unknown $A_s = x + jy$.

As an example, consider the case of a planar tag antenna at 915 MHz and $Z_a = 6.7 + 148.8j$, $\Gamma_1 = 1$ (open circuit) with $\sigma_1 = 0.0098\ \mathrm{m}^2$, $\Gamma_2 = 0$ (matched load) with $\sigma_2 = 0.0148\ \mathrm{m}^2$ and $\Gamma_3 = j$ (reactive load) with $\sigma_3 = 0.0146\ \mathrm{m}^2$ [10]. The result of the above calculation provides an exact value of $A_s = 0.6047 + 0.5042j$. That is close to the approximate value provided in [10], where A_s is graphically estimated on a Smith chart.

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