On the Design of Passive RFID Tags for ASK Modulation

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***Abstract*— Design of passive UHF RFID tag for ASK modulation is investigated. It is shown that tag antenna structural mode strongly affects the tag's backscattered field, shaping the phase and magnitude of the modulated signal. In contrast to prior art, the proposed circuit design can manipulate the effects of the tag antenna structural term, ensuring phase continuity of the backscattered field, which is a necessary condition for ASK modulation. Furthermore, the structural field can be favourably exploited, increasing the total backscattered power, by properly selecting the circuit's parameters within realistic values as shown herein. Identification range, maximum power transfer, BER and total backscattered power with respect to the parameters of the circuit are evaluated and optimised.**

I. Introduction

Radio Frequency Identification (RFID) has been continuously increasing its market share the past few years, replacing traditional short-range identification systems (e.g. barcodes) in typical tagging applications, while allowing the development of new range-demanding applications (e.g. tracing airport passengers, tracing goods in large facilities etc.). Future success of this highly promising technology depends on improving the range and performance of these systems, while reducing the cost of the tags and associated equipment.

In UHF RFID communications a tag modulates a continuous wave (CW) signal transmitted by the reader, by changing its load between two states, thus changing the phase or/and the magnitude of the backscattered signal that arrives at the reader [1]. Performance of the system depends on proper load selection for the two states of the tag, so as to ensure enough backscattered power at the reader and sufficient separation in the complex plane of the backscattered fields that correspond to the two states of tag-loading.

In addition, for passive tags, where no battery source exists, their circuits are driven from the transmitted power of the reader. The ability of the tag to "wake up" and store this power represents the main limiting factor for the identification range of high frequency RFID systems [1]—[3]. As a result, it is of critical importance to draw as much of the incident power as possible.

In this paper we focus on circuit-level tag design, in order to first maximize identification range and BER performance of the system. Rectification of the incident power in the tag's circuitry has been thoroughly analyzed in several works [1]—[7]. In this work, we focus on proper load selection of the tag in the two modulation-states, so as to optimize its performance. The novelty of this work is that we include tag-antenna structural mode in the design process. Antenna structural mode [8]—[10], though recognized as a quantity in the tag's backscattered signal [2], [11], is usually omitted in the literature from the tag-design process. In this work, we show the importance of this elementary parameter in the design process. We propose a circuit for ASK modulation that exploits the field and evaluates the performance of the tag for ideal and non-ideal conditions. Finally, the suitability of the proposed circuitry will be discussed and verified for typical values of all associated elements.

The solutions provided herein have been applied for ASK modulation. However, similar process can be expanded for BPSK modulation, which is also encountered in RFID systems.

II. Antenna Backscattering

The backscattered field by a tag's antenna can be expressed as the phase sum of two terms: a "*structural mode*" and an "*antenna mode*" term [8]—[11]. The structural term expresses the backscattered field when the tag antenna is connected to a specific reference load. Three typical selections of such reference loads found in the literature are [9]: *a*) short, *b*) conjugate-matched to antenna's impedance Z_a and *c*) matched to antenna's impedance. The expression for the backscattered field is given below:

$$E_S\left(Z_L\right)=\underbrace{E_S\left(Z_{ref}\right)}_{\text{structural term}}+\underbrace{\frac{I_{ref}}{I_r}\Gamma E_r}_{\text{antenna term}}\,. \qquad (1)$$

$E_S(Z_L)$ is the scattered field by the tag connected to load Z_L, $E_S(Z_{ref})$ is the scattered field when the tag is connected to reference load Z_{ref}, I_{ref} and I_r are the currents of the antenna when connected to loads Z_{ref} and Z_L respectively, E_r is the radiated field from the antenna when excited with current I_r and Γ an appropriate reflection coefficient that depends on the reference load.

The structural mode term reflects the behaviour of the tag as a scatterer, sizing the field that would be scattered by any object that has the same shape and is made of the same material as the antenna [9]. As a consequence, this term can be hardly predicted theoretically. However, it can be measured experimentally [12]. The structural term is independent of the load impedance connected to the tag's antenna in the two states of the tag and thus, is common to the tag's backscattered field in both states. It is important to be considered during the tag-design process, because it is added to the antenna mode term in the complex plane and thus, influences the backscattered field.

Adopting the most widely used reference load from Green [10], we take $Z_{ref}=Z_a^*$; so, the structural mode term expresses the backscattered field when the load equals the conjugate of the antenna's impedance Z_a. The physical interpretation is that at conjugate match, no backscattered power from an antenna is expected since the incident power is transferred to the load; hence, all backscattered power is "structural". After some manipulations, the tag's radar cross section (RCS) σ is given by [10]:

$$\sigma = \frac{\lambda^2}{4\pi} G_{tag}^2 \left|\Gamma - A_s\right|^2, \qquad (2)$$

where λ is the operating wavelength, G_{tag} is the tag-antenna's gain, $\Gamma = \left(Z_L - Z_a^*\right)/\left(Z_L + Z_a\right)$ and A_s quantifies the structural mode term. A_s can be evaluated graphically [12] or analytically [13] by measuring antenna RCS for three different loads.

A_s is often omitted in the related literature during the tag-design process [2], [11], claiming that this term doesn't influence Bit Error Rate (BER) performance of the system, since it is common in the backscattered field, regardless of the connected load. Even though this claim is correct, A_s strongly influences the backscattered power [13], as well as the modulation of the backscattered field. It was shown in [13] that apart from optimizing BER performance, total backscattered power maximization should be sought. Zero backscattered field can be measured by selecting a load such that $\Gamma=A_s$ in the complex plane, provided that $|A_s|\leq 1$ [10]. By neglecting A_s in the calculations, an inaccurate estimation of the backscattered field would be derived. The magnitude of A_s depends only on the size and the geometry of the antenna-scatterer.

III. Tag Design

As discussed in the introduction, the incident CW at the tag antenna is modulated by changing the tag's load between two values. Let Γ_i, i=1,2 denote the reflection coefficient for each state:

$$\Gamma_i = \frac{\left(Z_i - Z_a^*\right)}{\left(Z_i + Z_a\right)}. \qquad (3)$$

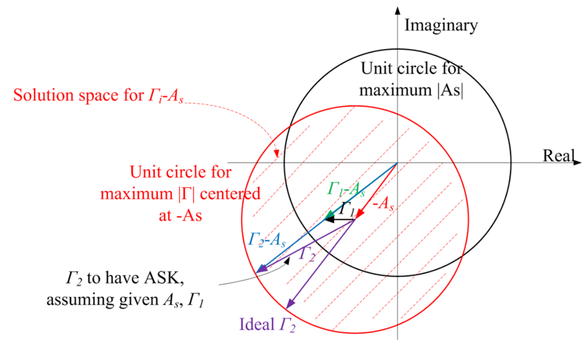

Fig. 1. Selecting the loads for ASK modulation.

The RCS for each state is given by (2), after substituting Γ with Γ_i. The backscattered field varies with Γ_i-A_s. Since $|\Gamma_i|\leq 1$, we can map the performance area for ASK modulation, as shown in Fig. 1. We start by drawing the common term -A_s, represented by a vector in the complex plane. Then, we draw a circle of unit-radius centered at -A_s. The surface enclosed by that circle represents the area, where Γ_1-A_s and Γ_2-A_s could belong. To have ASK modulation, the phase of Γ_1-A_s should equal the phase of Γ_2-A_s.

In the case of a passive tag, the most important parameter that affects the identification range of the system is to transfer the maximum possible energy to the rectifier. If the power is not large enough to power up the tag, then modulation can not take place. Therefore, the 1st design parameter is:

$$min\left\{\left|\Gamma_1\right|\right\} \Rightarrow max \text{ power transfer to the tag circuitry.} \quad (4)$$

The next two conditions, proven in [3] are:

$$max\left\{\left|\Gamma_1 - \Gamma_2\right|\right\} \quad (5)$$

$$max\left\{\sigma_1 + \sigma_2\right\} \quad (6)$$

$$\text{subject to } \angle\left\{\Gamma_1 - A_s\right\} = \angle\left\{\Gamma_2 - A_s\right\} \quad (7)$$

Eq. (5) ensures optimum BER while (6) guarantees maximum average backscattered power. Eq. (7) sets the necessary phase-equality condition to have ASK modulation.

IV. Circuit Design

The proposed circuit model for ASK modulation, by taking into account the condition (7), is shown in Fig. 2. Capacitor X_i and resistance R_i represent the series equivalent of the rectifier [3], [4]. To simplify, without loss of generality of the analysis, we assume that the tag antenna operates at resonance, hence an ohmic part is considered in the model, depicted as R_s. In the sleeping state of the tag - state 1- we consider an inductor with reactance X_L. In state 2 of the tag, the rectifier is cut off, while the reactance X could be either capacitive or inductive depending on A_s and is a key element of the design, responsible for proper phase manipulation.

Introduction of reactance X in the design is the key-difference from typical ASK equivalent circuits found in literature [3, ch. 5], [1, ch. 5], where in "State 2" a short is considered instead; the "short" ensures the desired Γ_2=-1 reflection coefficient that optimizes BER performance (since typically $\Gamma_1\approx 0$

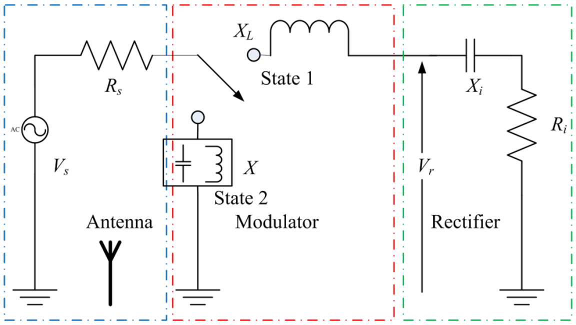

Fig. 2. Tag's simplified equivalent circuit.

and $|\Gamma_2\text{-}\Gamma_l|$ should be maximized), but the authors do not include A_s in the calculations. As the term A_s is subtracted from Γ_2 (equation (2)) the phase of the resulting field is no longer continuous with the phase of the field at state 1. Introduction of the proposed reactance "*X*" allows phase continuity of the field, by properly adjusting its value, while the magnitude of Γ_2 is still maximized thus preserving best BER performance.

Given the above tag model, the following design parameters are considered:

$$a = \frac{R_i}{R_s}, b = \frac{X_L}{X_i}, d = \frac{X}{X_i}, Q_i = \frac{X_i}{R_i}. \quad (8)$$

By analysis of the circuit of Fig. 2, we have at state 1 the voltage V_r at the rectifier in the following form:

$$\frac{V_r}{V_s} = \frac{a(1 - jQ_i)}{1 + a + jaQ_i(b-1)}, \quad (9)$$

where V_s represents the equivalent voltage source resulting from the incident field at the antenna. By substituting in (3), the reflection coefficient at state 1 is:

$$\Gamma_1 = -\frac{(1-a) - jaQ_i(b-1)}{(1+a) + jaQ_i(b-1)}. \quad (10)$$

The reflection coefficient at state 2 is:

$$\Gamma_2 = -\frac{1 + jadQ_i}{1 - jadQ_i}. \quad (11)$$

The power that is transferred to the rectifier at state 1 P_{rect} is:

$$P_{rect} = \left(1 - |\Gamma_1|^2\right) P_{tag}, \quad (12)$$

where P_{tag} is the power at the tag antenna and Γ_1 is the reflection coefficient given in (10). We denote antenna structural mode as: A_s=A_{sr}+jA_{si}. The radar cross section (RCS) σ_i of the tag in the two states of the switch is given by (2). A closed form expression to calculate A_s from three values σ_1, σ_2 and σ_3 of the antenna RCS is given in [13].

V. Ideal Performance

Ideally, from (4) we should have Γ_l=0. Thus the maximum power at the tag's antenna is transferred to the rectifier. In such a case we can only optimize the load at state 2 and thus set the desired value for Γ_2. In order to adhere to (7), the quantity Γ_2-A_s should be collinear to $-A_s$ (Fig. 1). To have maximum backscattered power, defined by (6), we must have:

$$max\{|\Gamma_2 - A_s|\} = 1 + |A_s|. \quad (13)$$

Equivalently, (13) gives:

$$|\Gamma_2| = 1, \ \langle\Gamma_2 = \langle -A_s. \quad (14)$$

To adhere to (5), assuming Γ_l=0, we have $max\{|\Gamma_1 - \Gamma_2| \mid \Gamma_1 = 0\} = max\{|\Gamma_2|\} = 1$. Notice that $|\Gamma_2| = 1$ was a necessary condition for maximum backscattered power, as shown in (14). Therefore, for $|\Gamma_2| = 1$, $\langle\Gamma_2 = \langle -A_s$, we can achieve maximum backscattered power and optimum BER performance, assuming that we have maximum power transfer at state 1 and ASK modulation.

VI. Practical Considerations

The rectifier comprises a multi-stage circuit of Schottky diodes connected to storage capacitors [1]—[3], [5], [6]. Schottky diodes are widely used due to the low cut-in voltage [5], [6]. The input impedance of the rectifier is quantified from the characteristics of the diodes [4], [6]. As the power at the antenna changes, the input impedance of the rectifier also changes, due to the nonlinear diode I-V characteristic. Power matching to the antenna is typically sought at the minimum power reception level. Generally, perfect matching of the antenna's radiation resistance R_s with the rectifier series resistance R_i may not be possible (a≠1). Assuming X_L is matched to X_i, we have b=1 and (10) becomes:

$$\Gamma_1 = -\frac{1-\alpha}{1+\alpha}. \quad (15)$$

By substituting (10) and (11) in (7) and solving for d, we get a single solution that ensures ASK for any a:

$$d = \frac{-Q_i + aQ_i - A_{sr}Q_i - aA_{sr}Q_i}{2aA_{si}Q_i^2} + \frac{\sqrt{4aA_{si}^2Q_i^2 + (Q_i - aQ_i + A_{sr}Q_i + aA_{sr}Q_i)^2}}{2aA_{si}Q_i^2} \quad (16)$$

Since the values of a, b and d are set, the remaining design parameter is Q_i. The magnitude of (9) for b=1 is:

$$\left|\frac{V_r}{V_s}\right| = \frac{a}{1+a}\sqrt{1+Q_i^2}. \quad (17)$$

V_r expresses the voltage at the input of the rectifier, which is desired to be greater than the cut-in voltage of the diodes that compose the rectifier (0.3V-0.6V), though a diode with as low as 0.09V cut-in voltage was reported in [6]. Hence, one is tempted to arbitrarily increase Q_i, in order to ensure sufficiently high voltage. However, Q_i also represents the quality factor of the R_i-X_L-X_i series circuit at resonance and is connected to the desired operating bandwidth Δf of the tag and the carrier frequency f_0 by the following equation:

$$Q_i = \frac{f_0}{\Delta f}. \quad (18)$$

Therefore, Q_i is limited by the desired operational bandwidth. For example, a UHF tag must be operational globally (since the attached product could be shipped and tracked anywhere), therefore between 858MHz-930MHz. By substituting

f_0=894MHz and Δf=72MHz, Q_i should be smaller than 12.4 to achieve the desired bandwidth.

Input impedance values of commercially available UHF band RFID chips are given in [7]: R_i ranges from 3Ω to 77Ω, and X_i from 100Ω to 285Ω, while Q_i of the reported tags ranges from 1.3 to 43.

A. Applicability of the Proposed Design

In order to demonstrate the operation of the proposed circuit, let's evaluate the performance of a measured tag-antenna with structural mode A_s=0.6047+j0.5042 [12]. We assume Q_i=10 and that a changes from 0.5 to 5. By substituting in (16) we calculate the proper value of d to ensure phase continuity of the backscattered field in the two states of the switch. Then from (15) and (11) we calculate Γ_i. The resulting vectors Γ_1-A_s and Γ_2-A_s are given in Fig. 3. An example showing Γ_2 and Γ_1 for a=0.5 is also shown in dotted vectors. Notice how reactance X, calculated from (16) adjusts the phase of the backscattered field at state 2 so that it equals the phase of the field at state 1, taking into account the mismatch between tag-antenna and rectifier. The difference (Γ_2-Γ_1), which is crucial for the BER performance of the system, is also given in Fig. 3 and reaches its maximum value for a=1.8.

B. Range vs. Voltage at the Rectifier

The voltage V_s (see the circuit in Fig. 2) depends on the available power density at the tag's location and the ability of the tag's antenna to "capture" it. This property is mapped in the tag's antenna gain G_{tag} and radiation resistance R_s: Assuming b=1, and a=1 for the equivalent of Fig. 2, we have:

$$\frac{V_s^2}{R_s+R_i} = P_{tag} \underset{R_i=R_s}{\Rightarrow} V_s = \sqrt{(2R_s)\underbrace{P_tG_tG_{tag}\left(\lambda/4\pi r\right)^2}_{P_{tag}}}\,. \qquad (19)$$

G_{tag} and R_s typically take small values, because of the small size of the antenna.

By combining (19) with (17) and solving for r, we can evaluate the maximum identification distance r_{max} at which a tag can marginally "wake-up", as the rectifier operates at the cut-in voltage of the diodes V_{r_min}:

$$r_{max} = \frac{\lambda}{4\pi}\sqrt{P_tG_tG_{tag}}\,\frac{\sqrt{2R_s}\sqrt{1+Q_i^2}}{V_{r\_min}}\,\frac{a}{(1+a)} \qquad (20)$$

Range is proportional to Q_i, the square root of the antenna's resistance R_s and inversely proportional to V_{r_min}. In Fig. 4, we assume P_tG_t=35.17dBm (maximum EIRP in Europe), G_{tag}=0dBi, frequency f=866MHz, maximum power transfer (a=1) and plot the maximum range for decreasing V_{r_min} and 4 combinations of R_s and Q_i. R_s is typically a few Ohms, due to the small size of the tag's antenna, while Q_i cannot exceed 12.4, due to the desired operational bandwidth. Hence, the most reasonable combinations for practically achievable tag-designs are those with R_s={5,10}Ω and Q_i=12. Notice that these values can be well matched to the input impedance of the rectifier [7]. R_s=25Ω is given as a reference, demonstrating the improvement in range for an antenna with increased radiation resistance, while Q_i=20 is given as an alternative design, where a high-performance tag is desired to operate in a smaller bandwidth (e.g. only in the US licensed band).

C. Backscattered Power

The mean backscattered power P_{bsct} at a monostatic reader is given by:

$$P_{bsct} = \frac{P_tG_t\dfrac{A_{eff}}{\left(4\pi r^2\right)^2}\sum_{i=1}^{2}\sigma_iT_i}{\sum_{i=1}^{2}T_i}, \qquad (21)$$

where T_i is the time that the tag is connected to load i.

Assuming that T_1=T_2, we find that the mean backscattered power P_{bsct} is given by:

$$P_{bsct} = \underbrace{4P_tG_t^2G_{tag}^2\left(\frac{\lambda^2}{4\pi}\right)^2\frac{1}{\left(4\pi r^2\right)^2}}_{P_0}\left\{\frac{\left|\Gamma_1-A_s\right|^2+\left|\Gamma_2-A_s\right|^2}{8}\right\} \qquad (22)$$

or:

$$P_{bsct}/P_0 = \left\{\frac{\left|\Gamma_1-A_s\right|^2+\left|\Gamma_2-A_s\right|^2}{8}\right\} \qquad (23)$$

By substituting, the "ideal" conditions expressed in (13) and (14), we have the normalized mean backscattered power for increasing $|A_s|$:

$$\frac{P_{bcst}}{P_0} = \frac{1}{4}\left\{\left|A_s\right|^2+\left|A_s\right|+\frac{1}{2}\right\} \qquad (24)$$

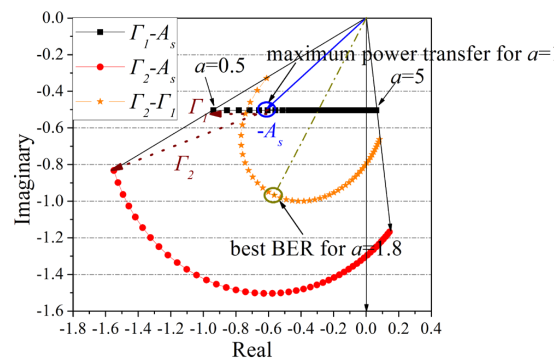

Fig. 3. Real & image of Γ_1-A_s and Γ_2-A_s versus a.

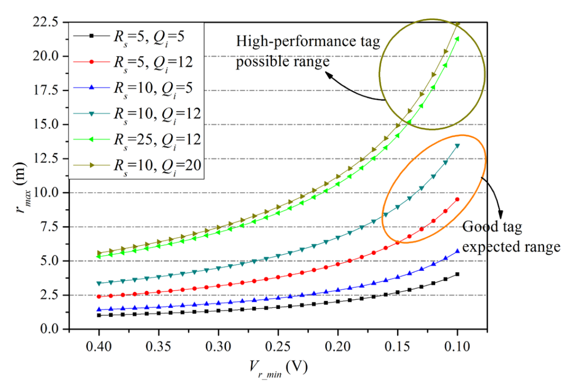

Fig. 4. Achievable range vs. minimum required voltage at the rectifier.

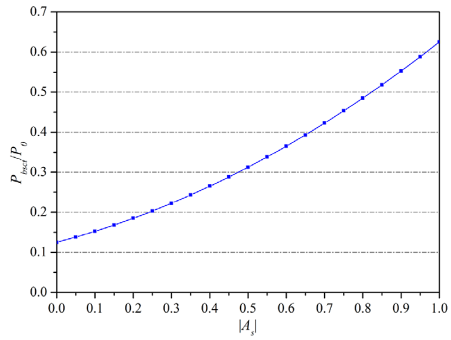

Fig. 5. Normalized mean backscattered power vs A_s for ideal performance.

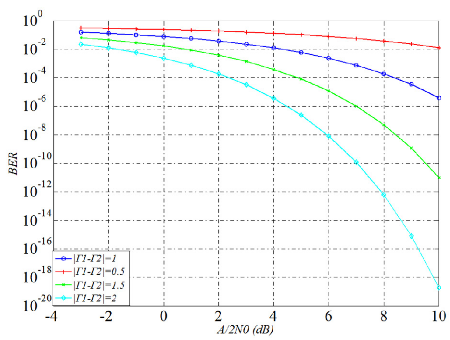

Fig. 6. BER performance for 4 cases of Γ_1-Γ_2.

Equation (24) is plotted in Fig. 5.

By substituting the measured value of A_s=0.6047+j0.5042, from [12], we have $|A_s|$=0.78 and P_{bsct}/P_0=0.47 from (24).

It is noted that as the sensitivity of the tag chips is reduced (nowadays reported at -18dBm [14]), resulting in reduced backscattered power at the reader, the passive tag's identification ability could become reverse-link limited instead of forward link limited. For example, in a hypothetical (or near-future) scenario of a tag with -22.5dBm sensitivity, the two-way path loss of a radiated 35dBm (EIRP) CW, reaching the tag at its minimum reception level, is 115dB. So, the backscattered power at the reader is only -80dBm, thus equals the sensitivity of today's high-end market-readers [15]. It is evident that in such cases, the power from the structural term could be vital for the successful identification of the tag.

D. Bit Error Rate Performance

The Bit Error Rate at the reader (BER) is given by [13], [11]:

$$BER = Q\left(\sqrt{\frac{|A|}{2N_0}}\left|\Gamma_1-\Gamma_2\right|\right), \qquad (25)$$

where $Q(x)=\left(1/\sqrt{2\pi}\right)\int_x^\infty e^{\left(-x^2/2\right)}dx$, A is a common term in the backscattered field in both states of the tag's load and accounts for the channel losses and N_0 is the expected power of the noise level at the reader, which is considered as complex zero mean circularly symmetric Gaussian random variable. In the case, where maximum power transfer is accomplished at one state of the tag, we have Γ_1=0 and therefore, the maximum achievable $|\Gamma_1$-$\Gamma_2|$ is 1.

As shown in Section IV-A, depending on A_s and the mismatch at state 1 (sized by a), $|\Gamma_1$-$\Gamma_2|$ ranges from 0 to 2. In Fig. 6, we plot (25) for increasing $A/2N_0$ for 4 values of $|\Gamma_1$-$\Gamma_2|$. It is found that BER performance is very sensitive to the difference between the reflection coefficients and special care should be given to accomplish $|\Gamma_1$-$\Gamma_2|$ at least close to 1.

VII. Conclusions

In this paper, a prototype circuit is proposed that can be optimised for passive UHF RFID tag with ASK modulation. It is shown that tag antenna structural mode has a twofold influence on the modulated backscattered field: *a*) it affects the phase of the field and *b*) it quantifies the backscattered power that arrives at the reader. In contrast to prior art, the proposed circuit can manipulate the effects of the structural term, ensuring phase continuity of the backscattered field, which is a necessary condition for ASK modulation. In the same time, its parameters can be appropriately selected within realistic values, as shown in this work, to achieve the desired performance with respect to a variety of metrics like: power transferred to the rectifier, backscattered power at the reader, or BER performance.

Acknowledgment

This research is funded by the Cyprus Research Promotion Foundation grant ΤΠΕ/ΟΡΙΖΟ/0308(ΒΙΕ)/13.

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