RFID Tag Analysis Using an Equivalent Circuit

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Abstract— **In this paper, we analyze one of the most common UHF RFID tag antenna structures, a T-matched dipole. We for the first time derive the closed-form solutions for the resonant frequencies of tag sensitivity and backscatter responses as functions of tag equivalent circuit parameters. We apply our general analysis to a 70 mm x 14 mm T-matched RFID tag with Monza R6 and show a good agreement between the model, the measurements, and the derived formulas.**

I. Introduction

RFID is a technology with a long history, and UHF RFID (also known as RAIN RFID) is a major part of it. A very common antenna used in RAIN RFID tags is a T-matched dipole shown in Fig. 1 (tag shown is E62 [1]). Such an antenna is essentially a loop coupled to a dipole, with an IC placed on the loop. This type of antenna provides a good broadband impedance match using only distributed traces and has also been known in general antenna world beyond RFID [2].

Fig. 1. Typical RFID tag with a T-matched antenna.

Tag performance can be characterized by tag sensitivity (also called threshold POTF, Power on Tag Forward) and tag backscatter (also called POTR, Power on Tag Reverse). A typical response of a T-matched tag is shown in Fig. 2 where both POTF and POTR are at tag threshold. Tag designers know that in such tags there are three resonant frequencies: two minima in POTF (frequencies f_a and f_b) and one maximum in POTR (frequency f_c). Locations of those frequencies are important for design of tags that work well on various materials and meet specifications such as ARC [3].

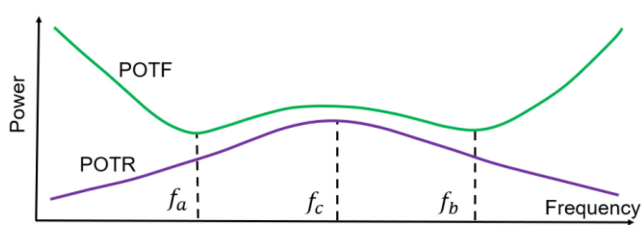

Fig. 2. Threshold POTF and POTR of a typical T-matched tag.

As it is known in RFID, T-matched tag antenna impedance can be approximated by various broadband equivalent circuits (see e.g. [4]). Fig. 3 shows two such circuits which both approximate the tag antenna complex impedance $Z_a = R_a + jX_a$, but one has a transformer and another instead has an equivalent T-network of inductors making it easier to use and analyze. An analysis of those circuits can explain tag POTF and POTR resonances locations and their dependence on tag parameters. Such analysis is the focus of this paper.

II. Analysis

The transformer-based circuit in Fig. 3 contains a series RLC-combo (components R_1, C_1, L_1) that represents tag dipole inductively coupled (with coupling coefficient k , $0 < k < 1$) to a parallel RLC-combo (components R_p, C_p, L_2) that represents tag loop loaded with RFID IC. Parallel Rp||Cp combination approximates chip threshold impedance in absorbing state. The circuit without a transformer has an equivalent T-network of three inductors, where $M = k\sqrt{L_1 L_2}$. Thevenin voltage source represents a voltage induced on the tag antenna ($|V_0|^2 = 8\, POTF\; G\; p\; R_a$, where V_0 is peak open-circuit RF voltage, G is the tag antenna gain and p is the polarization mismatch factor). Component values in both circuits are frequency independent and can be extracted using standard techniques if antenna impedance is known from either measurements or simulation [5].

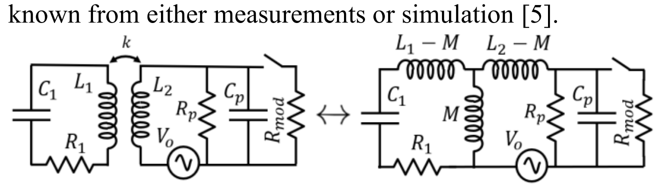

Fig. 3. Equivalent circuits of a T-matched tag antenna.

Let us define complex reflection coefficients ρ_c and ρ_m between the tag antenna impedance and the complex chip impedance in absorbing and modulating states as:

$$\rho_c = \frac{Z_c - Z_a^*}{Z_c + Z_a}, \quad \rho_m = \frac{Z_c \| R_{mod} - Z_a^*}{Z_c \| R_{mod} + Z_a}\ , \tag{1}$$

where $Z_c = R_c + jX_c$ is the complex chip impedance in absorbing state and R_{mod} is the modulation resistance.

To find the locations of POTF minima, let us recall that the chip sensitivity P_{th} is related to incident threshold POTF as

$$P_{th} = POTF_{th}\; G\; p\; \tau, \tag{2}$$

where $\tau = 1 - |\rho_c|^2$ is the tag impedance matching coefficient. For most tags, antenna gain G is a slowly changing function of frequency compared to τ and p is constant. Thus the minima of $POTF_{th}$ are defined by the resonant frequencies of the transfer function of either circuit in Fig. 3 when tag is in absorbing mode.

Let us assume that $R_p \to \infty$ (IC requires no power to turn on) and $R_1 \to 0$ (antenna has very low radiation resistance). This assumption does not change the resonant frequencies of the circuit transfer function and can be viewed as an application of the two extra element theorem [6]. Our left circuit then turns into two inductively coupled lossless LC tanks for which we can write an impedance matrix as:

$$\hat{Z} = \begin{bmatrix} \frac{1}{j\omega C_1}(1-\omega^2 L_1 C_1) & -j\omega M \\ -j\omega M & \frac{1}{j\omega C_p}(1-\omega^2 L_2 C_p) \end{bmatrix} \quad (3)$$

The resonances of the transfer function happen at frequencies where the determinant of the impedance matrix is zero (currents in either LC tank become infinite). This gives us a quadratic equation with ω^2 as a variable. Solution to that quadratic equation are the two frequencies of POTF minima, $\omega_a = 2\pi f_a$ and $\omega_b = 2\pi f_b$:

$$\omega_{a,b}^2 = \frac{\omega_1^2+\omega_2^2 \pm \sqrt{(\omega_1^2-\omega_2^2)^2+4k^2\omega_1^2\omega_2^2}}{2(1-k^2)}, \quad (4)$$

where $\omega_1 = 2\pi f_1 = 1/\sqrt{L_1 C_1}$ and $\omega_2 = 2\pi f_2 = 1/\sqrt{L_2 C_p}$ are the natural resonant frequencies of a dipole and a loop portions of the tag. In a general tag case, we can have $\omega_1 \geq \omega_2$ or $\omega_2 \geq \omega_1$. Note that in the case of weak coupling ($k \to 0$) we see that $\omega_a \to \min(\omega_1, \omega_2)$ and $\omega_b \to \max(\omega_1, \omega_2)$. To find the location of POTR maximum, let us recall that during tag backscatter the modulator (a transistor) turns on and off, applying R_{mod} in parallel with the antenna. The differential modulated backscattered power can be related to incident threshold POTF via backscatter factor K as

$$POTR_{th} = POTF_{th}\, K\,, \quad K = MG^2p^2\,, \quad (5)$$

where $M = 0.5|\Delta\Gamma|^2 = 0.5|\rho_c - \rho_m|^2$ is the modulation factor related to differential reflection coefficient $\Delta\Gamma$ that can be derived similarly to the derivation of modulated RCS (see e.g. [7]). The factor 0.5 is for 50% modulating duty cycle of the tag. Using the same assumptions for G and p and further assuming that modulating resistance is zero (this assumption does not change the frequency of POTR maximum), we see from (2) and (5) that the function whose maximum we need to find is defined by $\Delta\Gamma$ and τ and can be written as:

$$\frac{|\Delta\Gamma|^2}{\tau} = \frac{|Z_c|^2}{|Z_a|^2}\frac{R_a}{R_c} = \frac{R_p}{R_{pa}}, \quad (6)$$

where R_{pa} is the parallel resistance of the tag antenna: $R_{pa}||jX_{pa} = Z_a$. Because R_p is frequency independent, we can see that POTR reaches maximum when R_{pa} is at minimum. We can express parallel resistance R_{pa} as:

$$R_{pa} = \frac{L_2}{k^2 L_1 R_1}\left[R_1^2 + \omega^2 L_1^2\left(1 - k^2 - \frac{\omega_1^2}{\omega^2}\right)^2\right] \quad (7)$$

We can see from (7) that R_{pa} reaches minimum value at the frequency $\omega_c = 2\pi f_c$:

$$\omega_c^2 = \frac{\omega_1^2}{1-k^2} \quad (8)$$

This frequency gives the location of POTR peak. One can see from (4) and (8) that ω_c is a function of only dipole natural resonance frequency ω_1 and coupling coefficient k while ω_a and ω_b also depend on ω_2 (defined by chip capacitance and loop inductance). One can also show from (4) and (8) that for any ω_1, ω_2 and k, POTR peak is always contained between the POTF minima, i.e. $\omega_a < \omega_c < \omega_b$. These facts are empirically known to some RFID tag antenna designers but formulas (4) and (8) now provide a mathematical insight.

III. Example

Let us consider a practical RFID tag example: a 70 mm x 14 mm ER62 tag antenna (see Fig. 1) with Monza R6 IC [8]. We simulated this antenna on 2 mm thick cardboard material (ε =2.57, $\tan\delta$ =0.0717) using CST EM simulator and extracted the following equivalent circuit values: R_1 =77 Ohm, C_1=0.186 pF, L_1=162 nH, L_2=23 nH, k=0.19 that approximate tag impedance well as one can see from Fig. 4.

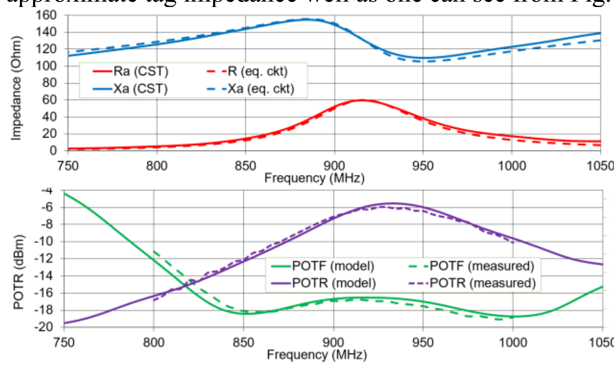

Fig. 4. Top: tag antenna impedance (CST and equivalent circuit).
Bottom: tag threshold POTF and POTR (model and measurements).

We measured this tag on the same cardboard material using our Voyantic [9] based setup described in [10] (autotune feature of Monza R6 was disabled to make POTF resonances more visible). Our modeled POTF and POTR calculated using (2) and (5) were in good agreement with measurements. We also calculated tag resonant frequencies from formulas given by (4) and (8) using R_p=1.56 kOhm and C_p =1.3 pF for IC impedance and found that f_a=842 MHz, f_c =934 MHz, f_b =1021 MHz (dipole and loop natural frequencies were f_1=915 MHz and f_2=920 MHz). Those values agree with tag resonant frequencies quite well as one can see from Fig. 4.

IV. Conclusions

In this paper, we derived closed-form solutions for T-matched tag resonant frequencies as functions of tag equivalent circuit parameters. We hope that this paper will be useful to a wide audience of RFID tag antenna designers who want a deeper understanding of T-matched tags to design better tags for various applications.

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