Equivalent Circuit Analysis of RFID Tags with Open Dipole Antennas

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***Abstract*—In this paper, we analyze UHF (RAIN) RFID tags with open dipole antennas using an equivalent circuit approach. We derive original closed form expressions for tag threshold sensitivity and backscatter resonances and mathematically analyze those. We also present a practical 42 mm x 16 mm RFID tag example, including modeling, simulations, equivalent circuit extraction and analysis, and measurements on dielectrics that represent practical use scenarios in real tagging applications.**

I. Introduction

In passive UHF RFID, also known as EPC Gen2, or RAIN (Radio-frequency IDentificatioN [1]), the choice of tag antenna, with specific gain and impedance match to the RFID IC (integrated circuit, or chip) over the desired band, is critical for the tag performance.

The simplest tag antenna is an open dipole. To reduce the size, open dipole antennas are usually folded or meandered or as shown in Fig. 1. The use of such antennas for RFID was analyzed in detail in early RFID works two decades ago [2-10].

Figure 1. Examples of RFID tags with open dipole antennas.

Open dipole antenna is a DC-open antenna. Such antennas were popular at the dawn of RFID because some of early tag ICs (such as the ones used in tags in [5-7]) used rectifier topologies that could not work with DC-short antennas.

Later ICs [11-14] used AC-coupled rectifiers that could work with any antennas, including DC-short antennas, such as T-matched antennas. Since then, a T-matching method became popular in tag antenna designs [15-28]. Today, majority of practical planar RAIN tags on the market use T-matched antennas. This type of antenna consists of a loop and a dipole and provides a good broadband impedance match using only distributed traces. It is commonly used in tags that are designed for ARC (RFID Assessment and Certification) RFID specifications [29, 30]. More than 98% of ARC certified tags currently use T-matched antennas.

However, even though T-matched antennas are good choice for RFID tagging scenarios like ARC that involve multiple item types, there exist niche applications where open dipole antennas have advantages over T-matched designs: even though their bandwidth is narrower than in T-matched designs, they can be made more compact because no inductive matching loop is needed. Examples include tags for specific item tagging [4-7] or miniature tags [8-9].

RFID tags can be characterized by threshold sensitivity and backscatter, also called threshold POTF (Power on Tag Forward) and threshold POTR (Power on Tag Reverse), terminologies introduced by Voyantic [31], now common in RAIN RFID industry. Tags with open dipole antennas have two resonant frequencies: one is the minimum of threshold POTF (frequency f_a) and another one is the maximum of threshold POTR (frequency f_c) as shown in Fig. 2, where R_a is antenna series resistance and X_a is antenna series reactance.

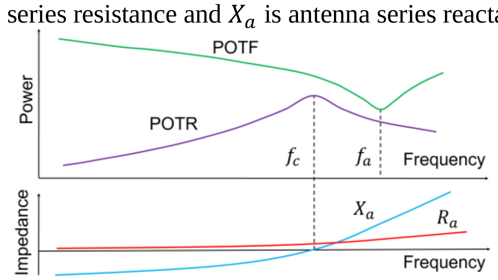

Figure 2. Threshold POTF, POTR, and impedance of open dipole tag.

In this work, we derive and analyze those frequencies, labeled as f_a and f_c to stay consistent with our previous work where we analyzed resonances of T-matched RFID tags [32].

II. Equivalent Circuit

A simple three-element circuit model of RFID tag with open dipole antenna is shown in Fig. 3. This is a narrowband model valid around the first dipole resonance. It is one of many circuits that can approximate dipole impedance, depending on the required frequency band of approximation [33-38].

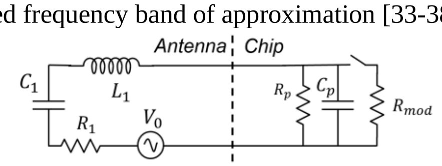

Figure. 3. Equivalent circuit of RFID tag with an open dipole antenna.

A series RLC-combo (components R_1, C_1, L_1) represents tag dipole resistance, capacitance, and inductance around its main resonance. It is loaded with a parallel RC-combo (components R_p, C_p) that represents RFID IC, modulated by R_{mod} when tag backscatters. A parallel $R_p||C_p$ combination approximates chip threshold impedance very well across wide range of frequencies. Thevenin voltage source V_0 represents a peak open-circuit RF voltage induced on tag antenna terminals. It can be found using Thevenin circuit for receiving antenna [39] as $|V_0|^2 = 8\, POTF\; G\; p\; R_a$, where G is the tag antenna gain and p is the polarization mismatch coefficient.

III. TAG ANALYSIS

In this section, we derive closed-form expressions for resonant frequencies f_a and f_c. First, let us define the natural resonant frequency of a dipole:

$$\omega_1 = 2\pi f_1 = 1/\sqrt{L_1 C_1}\,. \quad (1)$$

To find the frequency of threshold POTF minimum, let us recall from [32] threshold tag sensitivity $POTF_{th}$, given by

$$POTF_{th} = P_{th}/(G\,p\,\tau), \quad (2)$$

where P_{th} is chip sensitivity and coefficient τ is

$$\tau = 4R_a R_c/(|Z_a + Z_c|^2)\,. \quad (3)$$

In (3), $Z_a = R_a + jX_a$ is the complex antenna impedance and $Z_c = R_c + jX_c$ is the complex chip impedance in absorbing state. For most RFID tags and systems, antenna gain G is a slowly changing function of frequency compared to τ and polarization mismatch p is constant. Thus, the minimum of $POTF_{th}$ is defined by the resonant frequency of the impedance matching coefficient τ, or circuit transfer function. For the circuit in Fig. 3, that resonant frequency is defined by the series resonance of components L_1, C_1, and C_p and is given by

$$\omega_a = 2\pi f_a = \omega_1\sqrt{1+C_1/C_p}\,. \quad (4)$$

Now let us find the frequency of threshold POTR maximum. Threshold power backscattered by the tag ($POTR_{th}$) can be calculated from incident $POTF_{th}$(see [32]) as

$$POTR_{th} = POTF_{th} \cdot \frac{1}{2} G^2 p^2 |\Delta\Gamma|^2 \quad , \quad (5)$$

where $\Delta\Gamma$ is the differential reflection coefficient given by

$$\Delta\Gamma = |\rho_c - \rho_m|^2. \quad (6)$$

In (5), the coefficient ½ arises from assumed 50% duty cycle of tag modulation. In (6), ρ_m is the complex reflection coefficient between the antenna impedance and chip impedance in modulating state ($Z_c \parallel R_{mod}$) and is given by

$$\rho_m = (Z_c \parallel R_{mod} - Z_a^*)/(Z_c \parallel R_{mod} + Z_a). \quad (7)$$

Assume that the modulating resistance $R_{mod} \ll R_p$ (this is true for most RFID chips). Then we can derive that

$$POTR_{th} \approx P_{th}\, G\, p\, \frac{R_p}{R_{pa}}\,, \quad (8)$$

where R_{pa} is antenna parallel resistance ($Z_a = R_{pa}||jX_{pa}$). Let us use the same assumptions for G and p as above. Because R_p is frequency independent, we can see that $POTR_{th}$ reaches maximum when R_{pa} is at minimum. The parallel resistance R_{pa} of an open dipole antenna (represented by series RLC-circuit in Fig. 3) is given by

$$R_{pa} = \frac{1}{R_1}\left[R_1^2 + \omega^2 L_1^2\left(1 - \frac{\omega_1^2}{\omega^2}\right)^2\right]. \quad (9)$$

We can see from (9) that R_{pa} is minimum at the frequency

$$\omega_c = 2\pi f_c = \omega_1\,. \quad (10)$$

This frequency gives the location of threshold POTR peak and is identical to the dipole natural resonant frequency ω_1.

Fig. 4 shows the dependence of POTF resonant frequency ω_a (normalized to ω_1) as a function of chip capacitance C_p (normalized to antenna capacitance C_1).

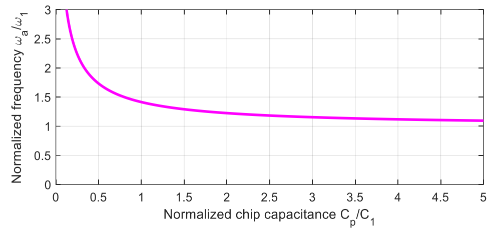

Figure 4. Normalized POTF resonant frequency of a tag with an open dipole antenna as a function of normalized chip capacitance.

One can see that POTF resonance ω_a of RFID tag with open dipole antenna is always higher than its POTR resonance ω_c (which is the same as ω_1). The two resonances converge if antenna capacitance is small compared to chip capacitance.

IV. ANTENNA EXAMPLE

Let us consider specific tag antenna example, a meandered 42 mm x 16 mm open dipole antenna shown in Fig. 5.

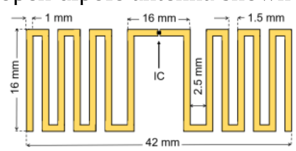

Figure. 5. RFID tag geometry.

We simulated this antenna using CST EM simulator [40] for air, plastic, and rubber (those materials represent ARC testing cases). We assumed that antenna is implemented using thin copper on 2 mil FR4 substrate. Besides air, parameters of two simulated dielectric materials (those are from Voyantic material reference set) are listed in Table II.

TABLE I. DIELECTRIC MATERIALS

Material	Size (mm)	Dielectric permittivity at 1.1 GHz	Dielectric loss tangent at 1.1 GHz
Plastic (polyoxymethylene)	130 x 130 x 4	2.96	0.045
Rubber	130 x 130 x 4	6.73	0.0247

Equivalent series RLC-circuit for this antenna can be extracted from the simulated antenna impedance using known methods [41-43]. At frequency ω_1, reactance is zero and hence

$$R_1 = R_a(\omega_1). \quad (11)$$

Now we can proceed with min-square error optimization over two remaining unknowns: L_1 and C_1 . Their values can be found by minimizing min-square error between simulated impedance and impedance produced by the equivalent circuit at a chosen set of discrete frequencies to get the best curve fit.

Extracted circuit component values are summarized in Table II for all three cases. In each case, equivalent circuit extraction was done for 300 MHz wide band, centered around antenna resonance where $X_a = 0$. Those resonances are 1099 MHz for air, 886 MHz for plastic, and 764 MHz for rubber.

Note that the antenna resistance R_1 is the highest on plastic, a material with highest dielectric tangent loss. As one can expect inductance L_1 remains approximately the same across the dielectrics while capacitance C_1 is strongly affected by the dielectric permittivity.

TABLE II. EQUIVALENT CIRCUIT COMPONENT VALUES

Component	Air	Plastic	Rubber
R_1 (Ohm)	12	18	12
L_1 (nH)	69	75	73
C_1 (fF)	308	443	616

Fig. 6 shows EM simulated and equivalent circuit-based impedance (using circuit in Fig. 3 with component values listed in Table II) of tag antenna on plastic. The equivalent circuit extraction band in this case was 736-1036 MHz.

The equivalent circuit approximates EM simulated antenna impedance very well within its bandwidth of validity. Note again that series RLC-circuit in Fig. 3 is a narrowband model valid only around the first dipole resonance (where $X_a = 0$) .

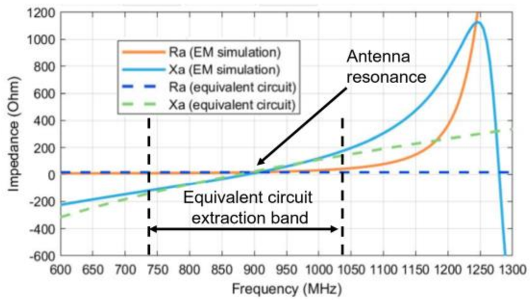

Figure 6. Antenna impedance on plastic: EM simulation and eq. circuit.

Gain of antenna in Fig. 5 on all materials, obtained from EM simulations (in the normal direction, orthogonal to the antenna plane), is shown in Fig.7. As one can see, it is indeed a slowly varying function of frequency compared to impedance.

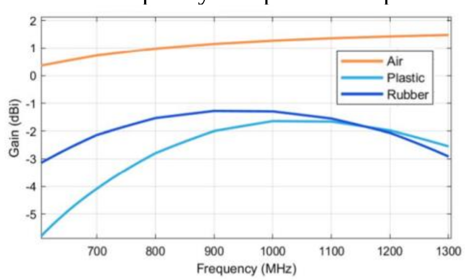

Figure 7. Gain (IEEE) of the antenna from Fig. 5.

V. EXPERIMENTAL RESULTS

We made the prototype of the tag in Fig. 5, using etched ½ oz copper on 2 mil FR4 substrate, with M700 series IC [44] mounted on it (autotune feature was disabled to make resonances more visible). The tag prototype is shown in Fig. 8.

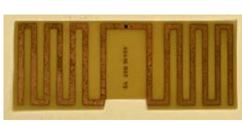

Figure 8. Prototype: 42 mm x 16 mm RFID tag.

We tested the prototype tag in our anechoic chamber measurement setup on all materials from the normal direction using Voyantic Tagformance Pro [45] as shown in Fig. 9.

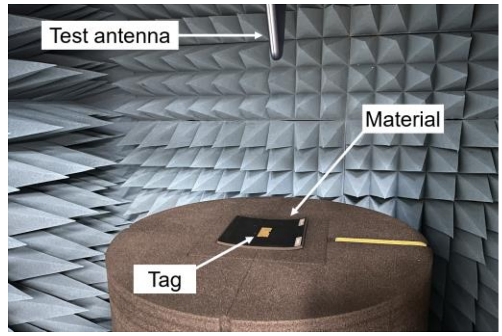

Figure 9. Measurement setup.

Measured threshold tag characteristics are given in Fig. 10. Our modeled $POTF_{th}$ and $POTR_{th}$ calculated using (2) and (5) and resonant frequencies calculated using derived formulas (4) and (10) are in good agreement with measurements.

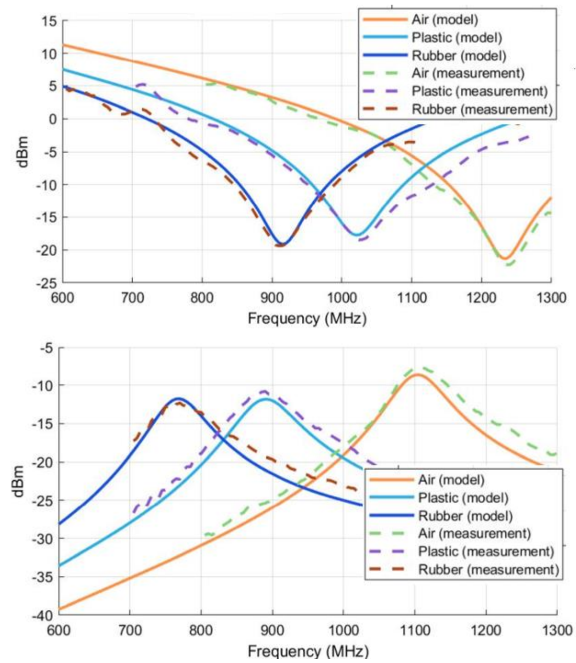

Figure 10. Modeled and measured threshold POTF (top) and threshold POTR of tag shown in Fig.8 on dielectric materials.

VI. DISCUSSION

One can see that on heavier dielectrics such as plastic and rubber (which are used in tests for many ARC specifications), POTF and POTR resonances of a tag shift significantly downwards in frequency, as expected.

Let us focus on FCC RFID band (902-928 MHz). If tag sensitivity (POTF) is important, this tag can be a desirable choice for applications like airline baggage tracking, where performance on rubber-like items is critical. If strong backscatter (POTR) is important, this tag can be a smart choice for tagging plastic-like items in retail store environment where low cost handheld readers with limited sensitivity may be used for reading tags.

VII. Conclusions

In this paper, we analyzed RFID tags with open dipole antennas using an equivalent circuit approach. We derived original closed form formulas for tag resonances and gave an example of 42 mm x 16 mm tag, including modeling, simulations, equivalent circuit, and measurements on various dielectrics representing practical use scenarios. We hope that this paper will be useful to RFID tag antenna designers who want to design open dipole type tags for various applications.

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