ANALYSIS OF CONSTRAINTS IN SMALL UHF RFID TAG DESIGN

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Abstract — Rapid growth of the application of the Radio Frequency Identification (RFID) technology to object identification has lead to a demand for compact, reliable and inexpensive RFID tags of good read range. Matching between tag antenna and chip impedances for maximum power transfer then becomes very important. Constraints on impedance matching in tags that derive from the reactive elements of the chip and antenna impedances are investigated. Following the analysis, a successful small UHF RFID tag design is presented.

I. INTRODUCTION

RFID is an emerging technology used for object identification by means of radio waves. Some of the common areas of application include the farming industry (tracking of tagged livestock), automated toll collection systems, and automation of various supply chains [1]. The focus of this paper is on passive RFID tags, i.e. those without an internal energy source and that rely upon the interrogation signal for their operating power.

The basic components of a tag are an antenna, a chip and most probably an impedance matching network. For maximum power transfer, and hence better performance of the tag, the impedance of the tag antenna should be matched with the impedance of the tag chip, and an impedance matching network is usually included to obtain an appropriate match. In practical applications we must achieve reasonable impedance match over an operating bandwidth that is established by the need to accommodate electromagnetic compatibility regulations in different world regions. In addition, when the tag antenna size is limited to an electrically small size, the reactance of the antenna complicates matching.

An analysis of these two problems is presented in this paper. The Bode-Fano theorem [2] is used in the analysis of the former problem. The antennas used in the analysis of the latter problem are a simple single turn circular loop antenna and a butterfly antenna. A small UHF RFID tag design is presented at the end of the latter analysis.

II. BANDWIDTH LIMITATION

A. Bode-Fano Limit

Fig. 1 shows a circuit with a real source impedance, a lossless matching network and a parallel RC load.

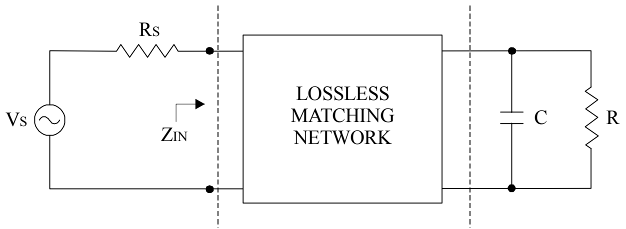

Fig. 1: A circuit with a lossless matching network and a parallel RC load

According to Bode and Fano, the fundamental limitation on impedance matching takes the form [2]

$$\int_0^\infty \ln \frac{1}{|\Gamma|} \, d\omega \le \frac{\pi}{RC} \qquad (1)$$

where Γ is the reflection coefficient of the load and its assumed lossless matching network with respect to the source impedance R_S, and R and C is the resistance and capacitance, respectively, that comes from the parallel RC load (Fig. 1).

Referring to equation (1), it can be observed that the maximum value of the integral is limited by π/(RC). To fully utilise the given limit of π/(RC) for a desired angular frequency bandwidth (Δω), $|\Gamma|$ should be 1 along the entire band except for the band of interest (Δω). This means a maximum mismatch outside Δω.

The best utilisation of π/(RC) is to keep $|\Gamma|$ constant (say at $|\Gamma|_{inband}$) over the band Δω, and unity outside this band as shown in Fig. 2.

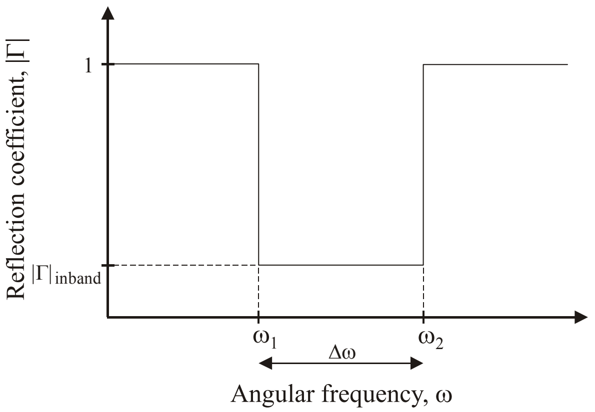

Fig. 2: Reflection coefficient for best utilisation of π/(RC).

Based on the case shown in Fig. 2, equation (1) becomes

$$|\Gamma|_{inband} \geq e^{-\frac{1}{2\Delta f RC}}. \qquad (2)$$

From equation (2), it can be observed that given RC, there will be a compromise between the maximum bandwidth and the maximum power transfer to the load. If matching is to be performed to satisfy a certain $|\Gamma|_{inband}$ (and hence, amount of power transfer), the bandwidth may have to be reduced. On the other hand, if matching is to be performed over a certain given bandwidth, the amount of power transfer to the load may have to be compromised.

B. Application of Bode-Fano Limit on RFID

The RFID bandwidths for European countries, United States of America (USA) and Japan are as shown in Table 1 below:

Table 1: Some allocated RFID bandwidths

Country	**Frequency in MHz**		**Bandwidth in MHz**
	Begin	**End**	
European countries	865	868	3
USA	902	928	26
Japan	950	956	6

Using these bandwidths, calculations of reflection coefficient are performed for three cases: (1) USA bandwidth only; (2) Europe, USA and Japan bandwidths [with gaps in between]; and (3) bandwidth for all of these frequencies without gaps. In the calculations we will assume first that R =1kΩ and C=1pF. The results of all three cases are summarised in Table 2.

Table 2: Minimum achievable reflection coefficients (R = 1 kΩ, C = 1pF)

Case	Minimum achievable reflection coefficient, $|\Gamma|_{inband}$
1	4.45×10^{-9}
2	6.25×10^{-7}
3	4.11×10^{-3}

All the values for $|\Gamma|_{inband}$ therein are small. This means the allocated bandwidths for RFID usage will not pose any theoretical limitations towards achieving a good impedance matching between the antenna and the chip of RFID tags.

Sometimes, in practice, when the RFID tag chip is less power consuming, the value for the resistance, R, can be assumed to be R = 10 kΩ. The cases presented above are re-evaluated for R = 10 kΩ. The results are recorded in Table 3.

Table 3: Minimum achievable reflection coefficients (R = 10 kΩ, C = 1pF)

Case	Minimum achievable reflection coefficient, $|\Gamma|_{inband}$
1	0.1462
2	0.2397
3	0.5773

From the values in Table 3, it can be observed that in practice, if the tag chip has R = 10 kΩ and C = 1pF, to maintain a constant reflection coefficient over a wider bandwidth, there is a noticeable limitation on the minimum achievable reflection coefficient. However the limitation is not severe, as even with a reflection coefficient of 0.5, 75% of the available power is transmitted to the load.

III. TAG ANTENNA SIZE CONSTRAINT

A. Estimation of RFID Tag Antenna Size

In this section, an analysis of RFID tag antenna size (and hence, the RFID tag size) required to produce reasonable match between the antenna and chip impedances of the RFID tag is presented. For simplicity a small single turn circular loop antenna without matching network is first considered. From the analysis, a conclusion will be made on whether it is feasible to design RFID tags by only adjusting the size of the RFID tag loop antenna, without having to include any impedance matching network, to achieve a reasonable matching between the antenna and chip impedances of the tag.

The single turn circular loop antenna has a loop diameter D and a wire of diameter d. The series equivalent circuit of this antenna has, assuming loss is negligible, a radiation resistance of R_r and an inductance of L, the formulae being given below (Equation (3) and (4)).

If the tag antenna and chip impedances are reasonably matched, the quality factor corresponding to the antenna, Q_{ant}, and the quality factor corresponding to the RFID tag chip, Q_{chip}, should be close to each other. The method of equating Q_{ant} and Q_{chip} is used in this analysis to estimate the tag antenna size. It has to be noted that although the values of Q_{ant} and Q_{chip} will be reasonably close for a matched circuit, having equal values of Q_{ant} and Q_{chip} does not always means the circuit is matched; after the estimation of the antenna size, the extent of match between the antenna and chip impedances must also be made.

The analysis starts with the calculation of Q_{chip}. Using the values R = 1 kΩ and C = 1 pF, the angular frequency bandwidth, $\Delta\omega = 1 \times 10^9$ rad/s. This corresponds to bandwidth, Δf = 159.15 MHz. Using a centre frequency, f_o, of 915 MHz, Q_{chip} is calculated to be 5.75.

Next, an expression for Q_{ant} in terms of antenna loop diameter, D, will be determined. The inductance of the circular loop antenna expressed in terms of the antenna loop diameter, D, and wire diameter, d, is

$$\text{Inductance, } L = \frac{\mu_0 D}{2}\left[\ln\left(\frac{8D}{d}\right) - 2\right] \qquad (3)$$

where $\mu_0 = 4\pi \times 10^{-7}$ H/m is the free space magnetic permeability. The radiation resistance R_r of this antenna can be expressed as

$$R_r = 20\pi^2 (\beta r)^4 \,\Omega \qquad (4)$$

where r = D/2 is the antenna loop radius and $\beta = 2\pi/\lambda$ is the free space propagation constant. If the ratio D/d is fixed to 10, Q_{ant} can be expressed in terms of D and β. It is found that

$$Q_{ant} = 36.4(\beta D)^{-3} \qquad (5)$$

For a frequency of 915 MHz, $\beta = 6.1\pi$ m^{-1} and hence, Q_{ant} is 5.17×10^{-3} D^{-3}.

Equating Q_{ant} with Q_{chip}, the loop diameter, D, of the antenna is found to be 9.65 cm. This is the size of the antenna as well as the approximate size of the RFID tag. With this size, the antenna has, using the assumed formulae, R_r = 144.29 Ω and L = 144.43 nH. The inductance will give a reactance, X_L = 830.34 Ω.

The parallel R = 1 kΩ and C = 1 pF of the tag chip gives a total impedance with resistance R' = 29.37 Ω and capacitive reactance $X_{C'}$ = 168.87 Ω. Comparing R_r and X_L found above with R' and $X_{C'}$, it can be observed that the circuit has not been well matched, with values of R_r and X_L approximately five times the values of R' and $X_{C'}$ respectively. For a matched circuit, $R_r + jX_L$ should be the conjugate of $R' - j X_{C'}$. In addition, for a frequency of 915 MHz with wavelength, λ, of approximately 33 cm, the size of the antenna is considered to be too large for the assumptions underlying equation (4) to apply. Thus the design is unsuccessful on two counts.

In practice, the tag chip may have R = 10 kΩ and C = 1 pF. If this is the case, the loop diameter, D, of the antenna is found to be 4.48 cm. The difference between the tag antenna and chip impedances is smaller compared to the case when R = 1 kΩ and C = 1 pF. However, the size estimated here is still not electrically small enough for the assumption under which the design is based to apply.

From this analysis, it can be concluded that for a small loop antenna which the size is always restricted to be less than λ/10, Q_{ant} will be large compared to Q_{chip}, and sufficient operating bandwidth for the applications discussed earlier will not be obtained.

B. An Example of A Simple RFID Tag

The RFID tag presented in this section consist of a chip and a butterfly antenna with a tuning strap which functions as a matching network (Fig. 3).

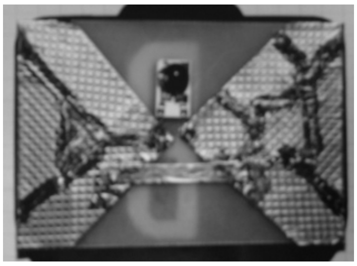

Fig. 3: A RFID tag with a simple matching network.

This structure has the advantage that it is practical to model the resistance and reactance behaviour of the antenna over a wider range of sizes than was used in the loop antenna design.

The butterfly antenna is made from tin-plated copper foil and has an equivalent circuit of a resistor with radiation resistance R_r, a capacitor with capacitance C_{ant} and an inductor with inductance L_{ant} in series. The tuning strap is made from copper foil and is equivalent to a resonating inductor L_{match}.

The capacitive reactance of the butterfly antenna is larger than its inductive reactance, hence the net reactance is a capacitive reactance, and converting all the elements in the circuit to a parallel configuration, the circuit can be simplified to the circuit shown in Fig. 4, where the resistor with resistance R_r' and the capacitor with capacitance C' in parallel are now the new equivalent circuit of the butterfly antenna.

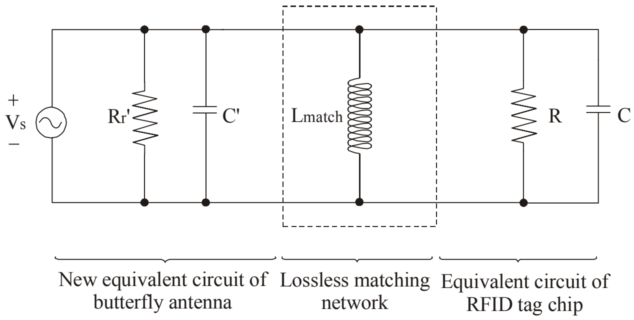

Fig. 4: Simplified circuit of RFID tag with a simple matching network

The values of R_r' and R are very close to each other. Hence, only an inductor (the copper strap that connects the wings of the butterfly) is needed in the matching network to tune the antenna and chip capacitances, and therefore achieve a satisfactory match between the tag antenna and chip impedances. The inductance of the inductor in the matching network is determined using empirical method. Only a simple short length of coaxial cable, with one end connected to the network analyser and another end terminated in a small loop, is needed (Fig. 5). The loop end of the coaxial cable is brought near to the copper strap (inductor) to examine the response of the RFID tag to magnetic field excitation, and from here, the resonance point is determined. If the resonance point or the response at this point is found to be unsatisfactory, the length of the copper strap can be adjusted accordingly.

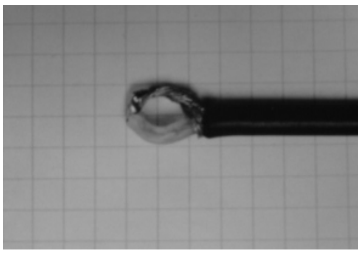

Fig. 5: A simple small loop used to determine resonance point of RFID tag

The RFID tag presented in this section has many advantages. One of the main advantages is the simplicity of the matching network. Due to the nature of the type of the antenna used, a complex matching network is not required and empirical method can be used in designing the matching network. In addition, the distance from the centre of the tag to the edge is short compared with a wavelength, which means the antenna size will not be so as to require an excessively complex equivalent circuit.

IV. Conclusion

This paper has presented analyses of two constraints in RFID tag design in terms of impedance matching between the tag antenna and chip impedances. It can be observed that, in practice, if impedance matching is performed over a certain bandwidth, there is a limit to obtaining the best reflection coefficient. Also, this paper has shown that there can be difficulties in impedance matching when the RFID tag antenna size is limited to be electrically small. A small RFID tag design with a simple matching network has been presented at the end of the paper.

References

[1] J. Grasso, "The EPCglobal Network: Overview of Design, Benefits, & Security", EPCglobal Inc. Position Paper, 24 September 2004.

[2] R.M. Fano, "Theoretical Limitations on the Broadband Matching of Arbitrary Impedances", Research Laboratory of Electronics, Massachusetts Institute of Technology, Technical Report No. 41, 2 January 1948.