Small UHF RFID Label Antenna Design and Limitations

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INTRODUCTION

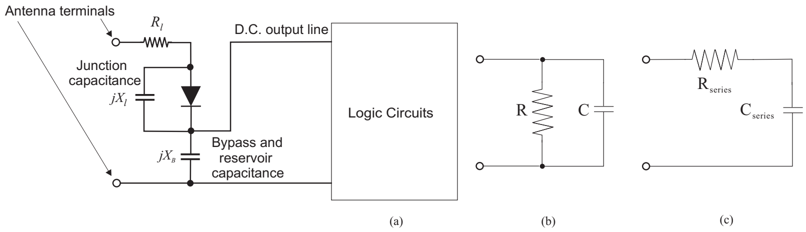


Fig. 1 An RFID IC. (a) IC schematic, (b) parallel equivalent circuit of the chip input impedance, (c) series equivalent circuit of the chip input impedance.

Radio Frequency Identification (RFID) is emerging as an unrivalled contender for automatic object identification technology, its adoption being driven primarily by the potential cost savings in the application of the technology to supply chain management [1]. In general RFID system components include RFID labels, Interrogators (transceivers) and backend control and data collection systems [2]. The mass utilization of RFID technology is hindered by the cost of RFID labels. The cost of producing a label can be separated into IC design, IC manufacture, antenna manufacture, antenna and IC assembly, and packaging. Significant barriers to reducing the cost are the lack of a streamlined process for attaching a RFID label antennas to RFID ICs (about 0.25 mm^2 in size) and the cost of manufacturing antennas, which currently cost around 3 - 4 US cents per label. Hence this paper focuses on low cost passive RFID labels with the aim of reducing passive labels costs.

Large antennas, albeit providing greater reading range, will cause greater interference with neighbouring antennas on RFID labelled items. In addition item sizes and the available area for attaching RFID labels places limitations on the size of possible antenna designs. The latter considerations have created an environment of miniaturization to create small and compact RFID label antennas of low cost. This paper considers specific limitations placed on designing small antennas for RFID labels for operation in the UHF band (the UHF RFID bandwidths for European countries, United States of America (USA) and Japan are as shown in Table 1).

The subject of small antennas has been considered in the past in notable publications [3, 4, 5 and 6]. This paper presents an analysis of the range of small antennas suitable for UHF RFID use, given cost and size limitations. The paper also outlines an analysis of the factors limiting the design of small antennas for UHF RFID labels taking into account limitations outlined in [7]. An example of a successful small UHF antenna design is analysed to outline a methodology for designing small UHF antennas of adequate performance albeit limited efficiency.

PRACTICAL RANGE OF SMALL ANTENNAS

An antenna with dimensions much less than the wavelength to which it is subjected to is constrained by limitations [4]. These limitations are similar for a capacitive or an inductive antenna consuming the same volume. Any advantage obtained may be as a result of the ability of the antenna to couple to its load.

Considering practicable antennas for RFID applications restricts us to mostly planar structures that can be attached to items, cases and pallets. In addition it is important to consider the RFID chip input impedance at the threshold of operation to realise a conjugate antenna impedance to achieve maximum power transfer. It is clear from Fig. 1(a) that the input impedance of an RFID chip is largely dictated by the junction capacitance of the rectification diode and as a result the input impedance of an RFID chip is largely capacitive with a typical R value of 1300 Ω in and a C value of 1.1pF (which is that expected from a passive RFID chip fabricated with CMOS technology at the threshold of its operation) resulting in a series equivalent circuit impedance of 18.95 – j155.8 Ω (Refer to Fig. 1(b) and Fig (c)). Maximum power transfer requirement dictate that the antenna impedance be a conjugate match to ensure the greatest possible performance (read range) from the RFID label. Hence a planar inductive antenna is preferred over a capacitive antenna to ensure maximum performance. In view of the above discussion a magnetic dipole antenna whose output impedance is largely inductive will form the most suitable structure for a small RFID label antenna.

RADIATION QUALITY FACTOR

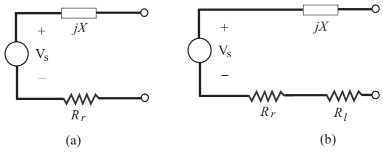
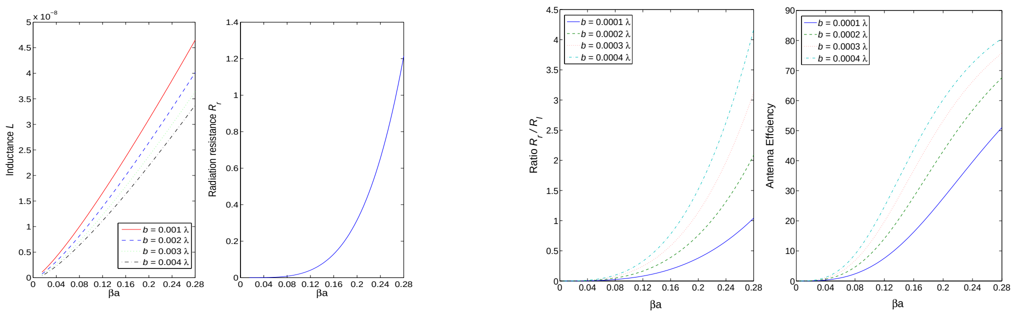


Fig. 2 Small antenna equivalent circuits, (a) an ideal lossless antenna (b) antenna in which the ohmic losses have been taken into consideration.



(a) (b)

Fig. 3 (a) Radiation resistance and the inductance of a small loop antenna, (b) Radiation resistance and loss resistance of a small loop antenna.

Fig. 2 shows equivalent circuits for an electrically small label antenna with an ideal voltage source V_s, a reactive element X, radiation resistance R_r and ohmic losses R_l. It shows that in both cases there is a radiation resistance in series with an antenna reactance. It has been shown that for ideal lossless and electrically small antennas, which would be enclosed completely by a sphere of radius r (both electric and magnetic dipole antennas), the radiation quality factor scales as follows [5].

$$Q_r = (\beta r)^{-3} + (\beta r)^{-1} \quad (1)$$

Equation (1) indicates a characteristically high Q_r for small antennas. This is as a result of a more rapid decline in radiation resistance with respect to the antenna reactance as the size of the antenna is made small.

$$R_r \ = \ 20\pi^2(\beta a)^4 \ \Omega \ \text{ and } L \ = \ \mu_0 a\left[\ \ln\left(\frac{8a}{b}\right) - 2\ \right] \text{H} \quad (2)$$

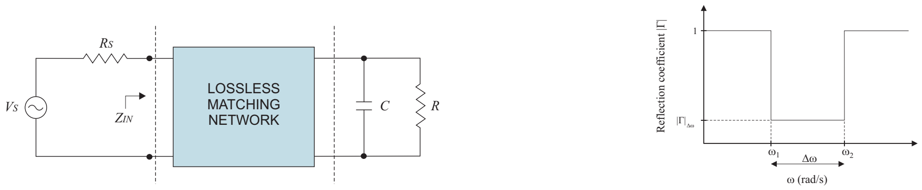
Consider the radiation resistance R_r, of a single turn small loop (inductive antenna), given in (2) and the inductance, L, of a single turn small loop, given in (2) expressed in terms of the antenna loop radius, a, and wire radius, b where $\mu_0 = 4\pi \times 10^{-7}$ H/m is the free space magnetic permeability [7]. Fig. 3(a) illustrates the radiation resistance and the inductance of a small single turn coil as a function of its size where, as the antenna (lossless) becomes very small, a relatively large reactance stands between the radiation resistance and any external load to which we might wish to match. It can be seen that the radiation resistance and the reactance are both sensitive to antenna size. However, it should be noted here that radiation pattern and the directivity of a small antenna is independent of its size [8].

The implications of a high Q_r for a label antenna are two fold. Primarily since Q_r is related to the antenna bandwidth BW, (where $BW = f_o/Q_r$ and f_o is the frequency of antenna operation) an increasingly larger Q_r signifies an increasingly smaller antenna bandwidth. This signifies a fundamental limitation on the useable bandwidth of the small antenna. Considering the largest available regulatory bandwidth given in Table 1, an upper limit of 35 for Q_r can be calculated for a small antenna with adequate bandwidth for operation in the widest UHF bandwidth provided in the United States of America. Secondly a large quality factor will cause the antenna to be easily detuned by environmental factors. Environmental detuning is a serious concern in RFID applications. These environmental factors may be as simple as the variation in the moisture content of a corrugated cardboard box. However the Q_r of a practical small RFID antenna design will be less than the minimum bound in (1) due to material losses.

$$R_l = \frac{a}{b}\sqrt{\frac{\omega\mu_0}{2\sigma}}\ \Omega \tag{3}$$

For a single turn loop antenna losses, R_l, can be characterised by (3) where ω is the angular frequency of operation and σ is the conductivity of the antenna material. Fig. 3(b) shows the relationship between R_r and R_l of a small antenna. It can be observed that the ohmic losses of a small antenna are much larger than the radiation losses of the antenna. This has two implications for RFID applications. The loss resistance while providing dampening effect to reduce the radiation quality factor and thus broadening the bandwidth of the antenna, also greatly reduces the efficiency of the antenna. Albeit the inefficiencies of small antennas, it is clear from Fig. 3(a) and Fig. 3(b) that a typical small antenna will not yield impedances of the order 18.95 + j155.8 Ω required to match to a typical RFID label IC with impedance of 18.95 – j155.8 Ω by adjusting the size of the antenna such that the antenna can still be considered as being electrically small.

RFID LABEL AND ANTENNA IMPEDANCE MATCHING



(a) (b)

Fig. 4 Bode Fano theorem. (a) A circuit with a lossless matching network and a parallel RC load, (b) Reflection coefficient for the best utilisation of π/RC.

Table 1 Minimum achievable reflection coefficients and regional frequency allocations.

Region	Frequency range (MHz)	Bandwidth (MHz)	R = 1500 Ω, C = 1pF	R = 2500 Ω, C = 500 fF
			Theoretical bound on $\lvert\Gamma\rvert_{\Delta\omega}$	Theoretical bound on $\lvert\Gamma\rvert_{\Delta\omega}$
USA	865 - 868	3	1.44×10^{-6}	2.08×10^{-7}
Europe	902 - 928	26	2.42×10^{-51}	1.24×10^{-58}
Japan	950 - 956	6	4.91×10^{-26}	1.11×10^{-29}
All regions	865 - 956	91	0.0214	0.0123

Fig. 4 (a) shows a circuit with real source impedance, a lossless matching network and a parallel RC load. According to Bode and Fano, the fundamental limitation on impedance matching takes the form [9]

$$\int_0^\infty \ln\frac{1}{|\Gamma|}\,d\omega \ \le\ \frac{\pi}{RC}, \tag{4}$$

$$|\Gamma|_{\Delta\omega} \ \ge\ e^{-\frac{1}{2\Delta f RC}} \tag{5}$$

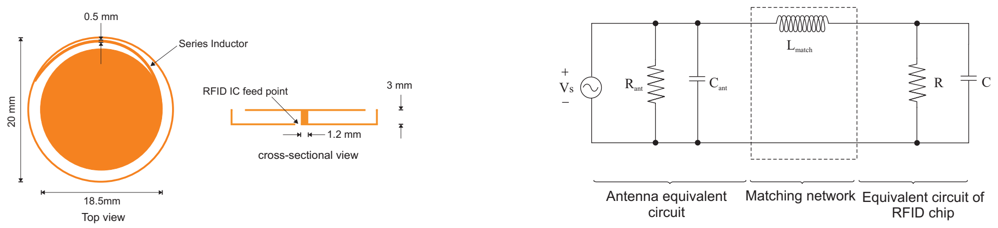
where Γ is the reflection coefficient of the load and its assumed lossless matching network with respect to the source impedance R_S, and R and C is the resistance and capacitance, respectively, that comes from the parallel RC load (chip impedance as shown in Fig. 2(a)). Equation (4) places a maximum limit on the integral to π/RC. In order to completely utilise the given limit of π/RC for a desired angular frequency bandwidth ($\Delta\omega$), $|\Gamma|$ should be unity along the entire band except for the bandwidth, $\Delta\omega$ under consideration, thus implying a complete mismatch outside $\Delta\omega$. Considering a minimum achievable mismatch over $\Delta\omega$ and thus a minimum bound on the reflection coefficient of $|\Gamma|_{\Delta\omega}$ over the bandwidth $\Delta\omega$ (refer to Fig. 4(b)) yields (5) which reveals that for a given RC load, there is a compromise between the maximum matching bandwidth and the maximum power transfer to the load.

If matching is to be performed to satisfy a certain acceptable $|\Gamma|_{\Delta\omega}$ (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. Using the bandwidths outlined in Table 1 calculations of reflection coefficient limit established in (9) are performed for the three regions: USA, Europe, and Japan and outlined in Table 1. The values for $|\Gamma|_{\Delta\omega}$ when we assume a chip resistance R of 1.5 kΩ and a chip capacitance C of 1 pF, are small and hence the allocated bandwidths for RFID usage will not pose any theoretical limitations towards achieving a good impedance match between the antenna and the RFID chip. However more recent advances in the fabrication of Schottky diodes and low power CMOS processes have yielded RFID chips with chip impedances represented by a resistance R of 2500 Ω with a parallel capacitance C of around 500 fF. The cases presented above are re-evaluated and the results are presented in Table 1. From the values in Table 1, it can be observed that in practice, if the tag chip has R = 2500 kΩ and C = 1 pF, the theoretically achievable minimum reflection coefficient is very small and thus presents no theoretical limit to the maximum power transfer to an RFID chip across the UHF RFID bands in the regions considered above.

SMALL ANTENNA DESIGN

Designing small antennas for RFID labels requires understanding the physical and theoretical limitations of the antennas. It is possible to overcome some of these limitations by manipulating the shape of small antennas to create a matching network as part of the antenna structure. Since small antennas can be viewed as an inductive or a capacitive structure this process is akin to physically creating lumped elements on an antenna structure. However due to size limitation only simple matching networks are possible (one or two element) and it is not possible to implement a complex structure on an already physically small antenna. A number of empirical methods can be used in designing the matching network.

The UHF antenna design for tagging metallic objects in Fig. 5(a) [11] is a small top loaded monopole above a ground with a series inductor to achieve a reasonable match to the RFID chip impedance. Fig. 5(b) shows and equivalent circuit of the RFID label with the matching network achieved by the inductive track. This is not a planar antenna design and thus more expensive to produce. However cost was not a factor in the design process however a more cost sensitive small antenna design for a passive RFID label based on the above technique can be found in [12].



(a) (b)

Fig. 5 (a) A top view and a cross-sectional view of a small capacitive antenna for tagging metallic objects (b) Simplified RFID label circuit with the Antenna in Fig 8, a matching network, and a RFID chip

Clearly the addition of a matching network reduces the Q_r of the circuit to near that of the quality factor of the chip, Q_{chip} which has a value of about 8 for a typical RFID chip. Thus the bandwidth of the antenna will be significantly increased albeit at the cost of large losses. However it is then possible to expect a bandwidth of around 110 MHz which is far more than that required for the broadest band available for RFID operations around the world (refer to Table1). Although in practice the Q_r will be further reduced due to the loss contribution, R from the RFID chip.

CONCLUSIONS

Small antenna design limits the designer to planar inductive structures due to cost limitations and the capacitive nature of the load impedance presented by an RFID chip. Consideration of an adequate size for a small antenna involves designing an antenna with input impedance that is a conjugate of the RFID chip however, achieving a match to the chips real impedance also effectively increases antenna losses. Nevertheless the added losses then ensure that the antenna has an adequate bandwidth despite being rather inefficient. We have also shown that there can be difficulties in impedance matching when the RFID tag antenna size is limited to be electrically small.

An interpretation of the Bode-Fano theorem provided a theoretical limit to the achievable power transfer between an RFID label IC and an RFID label antenna where for a given chip impedance (RC load), there is a compromise between the maximum matching bandwidth and the maximum power transfer to the load. We have also illustrated a practicable small UHF RFID label antenna designs and detailed the method of designing the antennas for adequate performance for UHF RFID use.

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