On the Design Considerations and Limitations of Passive RFID Tag Antennas

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1. Introduction

Passive radio frequency identification (RFID) system is an emerging solution to identify and track various objects now-a-days [1]. A basic RFID system consists of a reader, tag and a host computer. And the tag comprises of an antenna and a microchip called application specific integrated circuit (ASIC), both with complex impedances. The basic communication of passive RFID is based on backscattering. In this method, reader antenna sends a radio signal into the air to activate the tag and commands data from tag which then responds by backscattering its identification data back to the reader. As there is no internal source of energy in the tag's microchip in passive RFID tags, they will get all the energy for functioning from the electromagnetic radiation emitted by the reader as shown in Figure 1.

Proper tag antenna design comes of a paramount importance depending on the several significant parameters such as impedance matching between the antenna and tag chip, materials and locations of objects, cost, radiation pattern, antenna polarization etc. Several papers have dealt with the performance criteria in passive RFID tags as impedance matching concepts in [2], a practical antenna design considerations have been reviewed in [3], design of RFID tag antenna for metallic surfaces is discussed in [4] and performance of quasi-isotropic radiation pattern for broadband RFID tag antenna is also narrated in [5]. Since, most of the papers are concentrating on separate design issues for passive RFID tag antenna at different frequencies, there is a significant need to review the design considerations of passive tag antenna as a whole to provide a detailed insight to the design perspectives. And hence, this paper deals with the design considerations for the passive RFID tag antenna with a view to pin-pointing some limitations of the same to establish a bridge between the considerations and limitations in RFID research.

2. Design Considerations

Passive tag antenna design considerations involve tradeoffs between antenna types, sizes, frequency of operation, maximum attainable gain, bandwidth and antenna performance on different materials in different frequency ranges. To take a deep insight of these considerations, we further categorized the most important design considerations with minimum explanations necessary as below:

2.1 Antenna Types

Passive RFID tag antenna could be of several types depending on application scenarios. The antenna impedance, gain, detection ranges, radiation pattern, polarization etc. change with the types of the antennas used for a particular RFID application. For example, dual dipole antenna eliminates the reader orientation sensitivity problem because of its simplicity and omni-directionality. For passive tags, it is desirable that the tag antenna should receive the electromagnetic signal from the reader at right angle. Keskilanmi et al. [6] presented a new method of using text as meander line for size reduction of tag antennas. Folded microstrip patch antennas are excellent radiators for tagging challenging products such as cigarette cartons [4]. Therefore, choosing a particular antenna requires proper selection procedures based on the parameters of tag antenna mentioned above.

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2.2 Impedance Matching

As shown in Figure 2, a Thevenin equivalent lumped circuit of RFID tag is represented. Hence, $Z_a = R_a + jX_a$ is the complex antenna impedance and $Z_c = R_c + jX_c$ is the complex chip (load) impedance. Antenna impedance is typically matched to the high impedance state to the chip in order to collect maximum power. When $Z_c = Z_a^*$, the maximum power dissipated from the antenna at the chip is assumed to be P_a. Therefore we can write,

$$P_c = P_a \tau \qquad (1)$$

Where P_c is the amount of power absorbed by the chip from the antenna and τ is the power transmission co-efficient which directly characterizes the degree of impedance match between the chip and the antenna expressed as

$$\tau = \frac{4R_c R_a}{|Z_c + Z_a|^2} \qquad 0 \le \tau \le 1 \qquad (2)$$

According to Bode and Fano, the fundamental limitation on impedance matching takes the form [7]

$$\int_0^\infty \ln \frac{1}{|\Gamma|} d\omega \quad \le \frac{\pi}{R_c C_c} \qquad (3)$$

Here, to fully utilize the given limit of $\pi / R_c C_c$ for a desired frequency bandwidth ($\Delta\omega$), $|\Gamma|$ is the reflection coefficient which should be 1 along the entire band except for $\Delta\omega$. To keep the best utilisation of $\pi / R_c C_c$ over we need to keep the value of $|\Gamma|$ constant over $\Delta\omega$ such that,

$$|\Gamma|_{desired} \ge e^{-\frac{1}{2\Delta f R_C C_C}} \qquad (4)$$

It should be clearly understood from (4) that, there is a tradeoff between maximum bandwidth and maximum power transfer to the chip or load impedance. For example, RFID bandwidth used by Japan is in the range of 950-956 MHz which amounts to 6 MHz bandwidth. For a practical RFID tag antenna, a range of R_c and a fixed C_c value are taken and $|\Gamma|_{desired}$ is presented in Table 1. It represents how the reflection coefficients change after a certain change in the value of resistances while keeping capacitance fixed.

2.3 Radar Cross-sections (RCS):

One of the most prominent design considerations is the maximum distance called detection or read range at which tag receives just enough power to turn on and scatter-back. Using Friis free-space equation we can write for the detection range r as

$$r = \frac{\lambda}{4\pi} \sqrt{\frac{P_t G_t G_r \tau}{P_{th}}} \qquad (5)$$

Where λ is the wavelength, P_t is the power transmitted by the reader, G_t is the gain of the transmitting antenna, G_r is the gain of the receiving tag antenna, P_{th} is the minimum threshold power necessary to provide enough power to the RFID tag chip. For impedance matching with variable τ, attainable read range is shown in Figure 3 which represents how the improvement in the detection range can be obtained by better impedance matching.

Performance of RFID tags is monitored by its RCS. Hence, the power re-radiated by an RFID tag in the direction of the transmitter can be written as

$$P_{re-radiated} = \frac{4R_a^2}{|Z_a + Z_c|^2} P_a G_r \qquad (6)$$

Therefore the RCS of RFID tag can be calculated as

$$\sigma = \frac{P_{re-radiated}}{P_d} = \frac{4R_a^2}{|Z_a + Z_c|^2} A_e G_r = \frac{\lambda^2 G_r^2 R_a^2}{\pi |Z_a + Z_c|^2} \qquad (7)$$

Where P_d is the power density of electromagnetic wave incident to RFID tag antenna in free space expressed as

$$P_d = \frac{P_t G_t}{4\pi r^2} \quad (8)$$

And A_e is the effective area of the antenna given by

$$A_e = \frac{\lambda^2}{4\pi} G_r \quad (9)$$

The power P_a collected by the tag antenna is by definition the maximum power that can be delivered to the complex conjugate matched load:

$$P_a = P_d A_e \quad (10)$$

2.4 Size of Tag Antenna:

In UHF band, small-sized tag antennas are required to produce. Because the length of a half-wave dipole antenna is almost 16.5 cm in free space. But, as the size of the antenna is reduced, its efficiency and bandwidth decrease resulting in impedance mismatch. Meander line antennas recently are widely studied to reduce the size of the radiating elements by folding the wire continuously to reduce the resonant length for a given frequency. The size reduction in the process requires shortening ratio (SR) defined as

$$SR = \frac{\frac{\lambda_g}{2} - 2L_{ax}}{\frac{\lambda_g}{2}} \quad (11)$$

where λ_g is the wavelength of the operational frequency on the substrate where the antenna is manufactured and $2L_{ax}$ is the axial length of the meander line dipole antenna.

2.5 Surface Material Properties

RFID tags are usually attached to various objects for which surface materials are unknown. Tag detuning takes place depending on the properties of surface materials and thus the reading performances of tags such as readable range and reading stability change as an effect to antenna gain and impedance match degradation. An object can be RF transparent, RF absorbing, RF reflecting, or exhibit a combination of the three. Therefore, the tag antenna has to designed and optimized for a particular platform. For dielectric surface materials, the readable range decrease due to the frequency shift of the resonant frequency. The radiation efficiency also decreases based on the electrical property of the surface materials. Moreover, if the objects have high conductivities, as is the case for metallic objects, then this degradation of the reading performance becomes significant since the tangential electrical currents on the metal surface cancel out.

Low cost constraints and diversity of RFID applications lead to consider non standard materials to be used for both tag and antenna. Investigations are needed in order to characterize these materials.

2.6 Radiation Pattern and Antenna Polarization

Readable range of the tag antenna should not vary significantly due to changes in rotation angle to ensure consistent readability. For this reason, radiation pattern of tag antenna should be close to an isotropic pattern. High radiation efficiency is needed to extend the readable range with restricted system power. Gain for small antennas is dependent on the type of radiation patterns which can be omni-directional with a peak gain of 0 to 2 dBi or where the radiation pattern has a definite lobe and the peak gain might be 6 dBi.

Antenna polarization of the tag must be matched to that of the reader antenna for maximizing the range and can be characterized by the polarization matched coefficient (χ). Using circular polarized reader antenna with linearly polarized tag removes sensitivity to polarization but incurs additional 3 dB loss.

Costs and reliability are other important factors in design consideration of a tag which should be taken carefully.

3. Conclusion

As a whole, this paper explicitly describes the most important design considerations for passive RFID tags with theoretical and practical insights which will fill up the gap between requirements and limitations in designing effective tags for RFID applications.

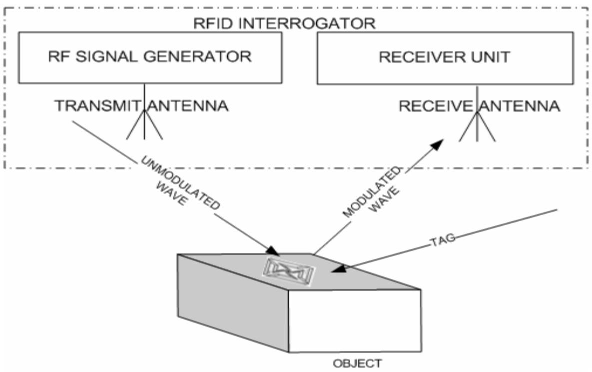

Figure 1: Passive RFID System Communication

Table 1: Minimum Reflection Coefficients for varying resistances

Resistance (KΩ)	Capacitance (Pico farad)	$\|\Gamma\|_{desired}$
7	1	6.758e-6
8	1	2.993e-5
9	1	9.523e-5
10	1	2.404e-4
11	1	5.127e-4
12	1	9.639e-4
13	1	5.319e-1

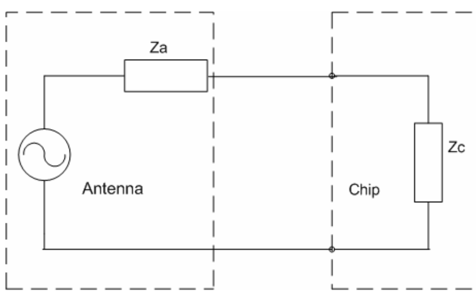

Figure 2: RFID Transponder Equivalent Circuit

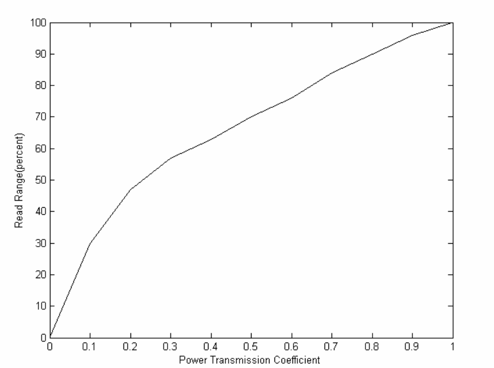

Figure 3: Normalized Read range vs Power Transmission Coefficient

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