Antennas for Chipless Tags Based On Measurement of Complex Impedance

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Abstract

Antenna design for chipless tags based on remote measurement of complex impedance is discussed. Such antennas need to be printable and de-embeddable from the terminating reactive network used for coding the tag information. We demonstrate that certain antennas have a low radar cross-section (RCS) under matched condition, while maintaining a fairly uniform RCS under various reactive terminations including open and short. Therefore, effect of such antennas can be de-embedded after being modeled as two-port networks whose parameters can be extracted using conventional Vector Network measurement techniques. The category excludes minimum-scatter antennas.

Index terms – Chipless RFID, Remote Vector Measurement, Complex Radar Cross-section, Minimum Scatter Antenna, Scattering Antenna

1. Introduction

The market for printed RF labels costing $0.01 or less, printed directly on a product or package, has prompted development of technology that allows printing the entire tag (including the antenna) with conducting ink. A previous work [1] has proposed terminating an antenna with a reactive network where the tag information is coded in terms of zeros and poles [2]. It [1] further proposes remote vector measurement of the terminating reactance to recover the coding information.

The present paper discusses antenna design issues for chipless tags as described above. We propose the nomenclature "Scattering Antenna" for an antenna terminated by a lossless reactance in this article. For such a device, all the power captured by the antenna should be re-radiated back as no energy is dissipated in the reactive termination. A simplified transmission line model provided in [1] describes the concept in equations (1) through 2(b).

Therefore, according to above premises, the scattering antenna should scatter back the same power irrespective of the type of lossless termination (including open and short), as they all produce a reflection coefficient of unity and the backscatter signal of [1] should be of constant envelope in absence of frequency selective fading.

However, a counter-example in the form of 'minimum-scatter antennas' [3,4] where no power is scattered back under open circuited condition demands further investigation to this assumption.

2. Scattering Property of Antennas

A Thevenin/Norton equivalent circuit is traditionally used to model antennas in transmit and receive modes [5]. The limitations of that model to interpret scattering phenomenon have been discussed in references [6-8]. The limitation is particularly obvious for antennas containing parasitic elements, where the scattered signal might approach zero under matched conditions [8].A passive backscatter tag containing a semiconductor chip (PBTSC) typically uses a dipole (or a variation of it) for its antenna, classifiable as 'minimum-scatter antennas' [4]. The semiconductor switch in the PBTSC switches the antenna port between open and matched termination conditions, resulting in amplitude modulation of the RCS [3]. Under open circuit conditions, RCS approaches zero for 'minimum scatter' (MS) antennas providing adequate depth of modulation for PBTSC.

Let us now discuss some desirable characteristics of a chipless tag antenna vis-à-vis antennas for PBTSC:

1. A MS antenna may not be the suitable candidate as RCS approaches zero under open circuit conditions.
2. Thevenin/Norton model has limitations to study scattering by antennas other than MS type.
3. The concept of antenna aperture may not be relevant as ideally no power is absorbed in a chipless tag. Complex RCS appears to be a suitable metric.
4. The physical mechanism through which an antenna absorbs power from an incident wave is destructive interference, i.e. the antenna scatters so as to cancel some of the incident fields [4]. Ideally we would prefer no

‘structural scattering’ [3,9] from a chipless tag, i.e. no scattering when the tag antenna is terminated by a matched load. This ensures that the energy incident on the antenna travels in its entirety to the terminal reactance and eventually gets reflected and re-radiated. Antennas with parasitic or passive elements have the potential to reach zero structural scattering [8] and can scatter even when the active element is open circuited [6], making them interesting for chipless tag application.

5. Antennas producing the same scattered power for both open and short circuit conditions are interesting to investigate as they fulfill a step towards achieving a ‘constant envelope’ signal where the magnitude of the Complex RCS stays constant for any reactive termination though changing in phase with frequency.

Therefore, it may be surmised that antennas containing parasitic or passive elements (including ground planes) are potential candidates for chipless tags.

3. Modeling of Scattering Antenna as Two-Port

Let us consider a Scattering Antenna (antenna terminated by reactance) operating in bistatic mode as in Fig.1(a). It is illuminated by a transmit antenna, and the scattered signal is received by a receive antenna. We propose that a non-minimum scattering antenna be modeled as a two-port network (Fig.1) whose parameters can be extracted using traditional Vector Network measurement techniques. We assume far-field behavior throughout.

The incident wave from the transmit antenna **a** is modeled as coming from a generator of impedance Z0 where Z0= impedance of free space (120π). $\gamma l1$ represent the forward propagation coefficient from the Transmit Antenna to the Scattering Antenna (tag), and $\gamma l2$ the return propagation coefficient from the tag to the Receive Antenna. The scattered wave **b** is generated due to reflection from the equivalent two-port network terminated by the unknown reactance Γt responsible for creating the phase-frequency profile. The objective is to de-embed the effect of the two-port network “error” network and determine Γt such that the tag identity can be ascertained.

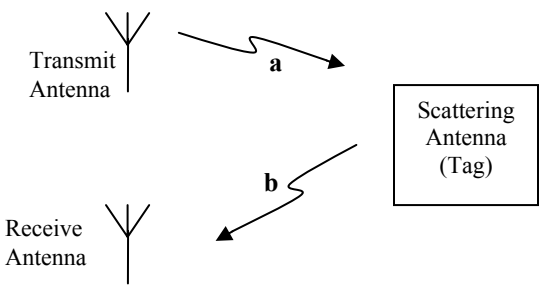

Fig.1(a) Scattering Antenna in Bistatic Mode

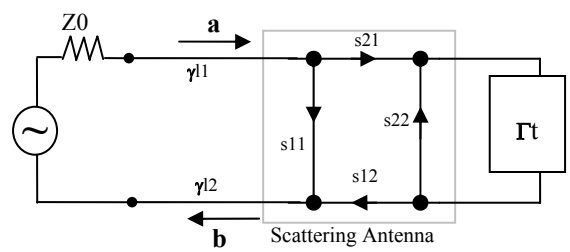

Fig.1(b) Scattering Antenna modeled as a 2-port

As discussed in Section 2, a certain class of antennas terminated by a matched load results in low RCS. This phenomenon occurs under resonant conditions when the antenna radiates power in transmit mode. Outside resonance, the antenna radiates negligible power in transmit mode, and scatters back finite energy even when terminated by the characteristic impedance, most of the backscatter energy being from “structural” scattering. Therefore, under resonant conditions, s11 in Fig.1 is expected to become small, and outside resonance s11 may approach unity. Also, a reactive termination will have negligible effect on the backscatter outside resonance.

4. Simulation

Printable antennas like a microstrip patch satisfy the requirements of Section 2, and will therefore be considered. Simulation using commercially available Electromagnetic Simulator (WIPL-D) [11] was tried on a rectangular patch on a finite ground plane with parameters shown in Fig.2. Infinite conductivity was assumed throughout. In the transmit mode, the patch was found to be resonant at about 5.9 GHz with a bandwidth of approximately 100 MHz with FP (Fig.2) as the feed point. The impedance at FP happened to be 50 Ω. The non-radiating edge was selected for feed point so as to disturb the radiating field as little as possible and. The patch was illuminated with linearly polarized wave parallel to Y-axis traveling in negative Z-direction, i.e. $\theta=0$, $\phi=\pi/2$ where θ and ϕ are elevation and azimuth angles respectively. The scattered electric field vector **E**, under far-field conditions, at co-ordinates (r,θ,ϕ) can be expressed as:

$$\mathbf{E}(r,\theta,\phi) = \mathbf{e}(\theta,\phi).\ \exp(-j\beta r)/r \tag{3}$$

where β is the propagation constant. The magnitude of RCS is defined as:

$$\sigma(\theta_i,\phi_i,\theta,\phi) = 4.\pi.[|\mathbf{e}(\theta,\phi)|^2/\ |\mathbf{E}_i(\theta_i,\phi_i)|^2] \tag{4}$$

where $\mathbf{E}_i(\theta_i,\ \phi_i)$ is the incident electric field vector in the θ_i,ϕ_i direction. Phase of the scattered field, using the origin as the phase reference point [12], can be expressed as

$$\Psi(\theta_i,\phi_i,\theta,\phi) = \arg[\mathbf{e}(\theta,\phi)/\ \mathbf{E}_i(\theta_i,\phi_i)] \tag{5}$$

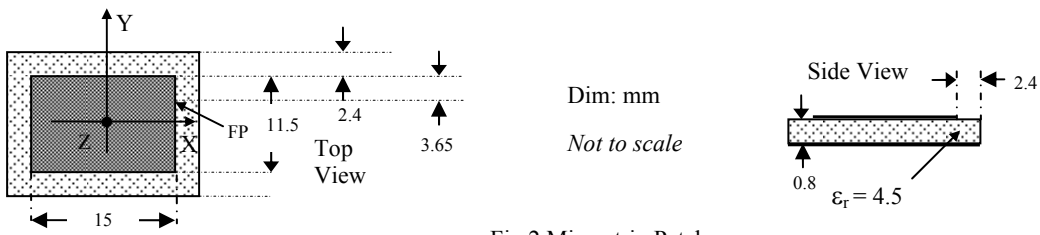

Fig.2 Microstrip Patch

Based on (4) and (5), we define a complex reflection coefficient as:

$$\Gamma(\theta_i,\phi_i,\theta,\phi) = \sqrt{\sigma(\theta_i,\phi_i,\theta,\phi)}.e^{i\Psi(\theta_i,\phi_i,\theta,\phi)} \tag{6}$$

The patch was successively terminated with an open (no termination), short and 50 ohm termination at FP, and the magnitude and phase of the co-polarized Γ as defined by (6) were computed. Let Γo, Γs and Γl be the complex reflection coefficient as defined in (6) due to open, short and load conditions for $\theta=\theta_i=0$ and $\phi=\phi_i=\pi/2$. The incident and backscatter waves are in negative and positive z-direction respectively, i.e. under bore-sight conditions. It was noted that $|\Gamma l|$ is significantly lower in the middle of the band compared to $|\Gamma s|$ and $|\Gamma o|$, indicating high amount of absorption by the termination resistor.

The following equations were used to calculate the parameters of the error network of Fig.1 from the calibration data, viz. Γo, Γs and Γl.

$$\gamma l1.\gamma l2.\mathbf{s}11 = \Gamma l \tag{7}$$

$$\mathbf{s}22 = (\Gamma o + \Gamma s - 2.\gamma l1.\gamma l2.\mathbf{s}11)/(\Gamma o - \Gamma s) \tag{8}$$

$$\gamma l1.\gamma l2.s21.\mathbf{s}12 = (1-s22).(\Gamma o - \gamma l1.\gamma l2.\mathbf{s}11) \tag{9}$$

We note that $\mathbf{s}11$ and $\mathbf{s}21.\mathbf{s}12$ occur de-normalized in conjunction with the term $\gamma l1.\gamma l2$.

In transmit mode, the antenna was almost perfectly matched to 50 ohms at 5.92 GHz, and reasonably matched at 5.96 GHz. However, at 5.88 and 6.00 GHz (band edges) matching is less effective with return loss in the order of 11 and 6.5 dB respectively due to the presence of significant reactive component. A similar general trend was observed in the value of $|\Gamma l|$. In other words, low backscatter is observed at frequencies where the antenna is well-matched to the external resistive load – 50 Ω in this case. As the matching becomes poorer, the backscatter increases due to increase in "structural cross-section". The de-embedding technique attempts to reduce the effect of the "structural" cross-section such that the effect of the terminating reactance can be observed accurately without being masked by the structural scatter. To verify the validity of the above model, a 1 nH inductor was introduced at the feed-point FP as the device under test (DUT). Γ was obtained for both bore-sight (θ=0, ϕ=90°) and a squint mode (θ= 15°, ϕ= 75°). Table 1 shows the recovered value of the inductance for bore-sight and squint mode after de-embedding the effect of the two-port error network. The corrected value of reflection coefficient was calculated according to

$$\Gamma corr = [\Gamma - \gamma l1.\gamma l2.\mathbf{s}11]/[\gamma l1.\gamma l2.\mathbf{s}21.\mathbf{s}12 + s22.(\Gamma - 1)] \tag{10}$$

We observe that the percentage error is low in the middle of the resonance when the structural scattering is least and therefore effect of the error network small. Therefore, to construct a successful Scattering Antenna (tag), the input impedance should have a large resistive (dissipative, i.e. radiation resistance) part compared to the near-field reactive part. We also note that using error network parameters for bore-sight, we could successfully extract the DUT even in squint mode due to the wide beamwidth of the scattering patch.

Table 1: Extracted value of DUT (1 nH inductor)

Freq GHz	L nH	% error	L nH	% error
	Bore sight		Squint mode	
5.88	0.968	3.2	0.994	5.6
5.92	1.001	0.05	0.998	0.2
5.96	0.997	0.3	1.005	0.5
6.00	0.966	3.3	0.993	0.7

Conclusion

A microstrip patch was modeled as a two-port network, by application of Vector Network calibration techniques, with a motivation to de-embed its structural scattering. Simulation indicated successful characterization of a DUT connected to the antenna port, thus making the device useful as a chipless RFID tag. The antenna bandwidth need to be increased to few GHz to encode forty or more bits in the tag [2]. Impedance level for feed point needs to be optimized for measurement in presence of impairments like multi-path. In general, the antenna may be considered as an N-port device for applying as many reactive terminations. There is also a motivation to develop a generalized theoretical approach for synthesis of antennas with low structural scattering.

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