Differential RCS of RFID tag

P.V. Nikitin, K.V.S. Rao and R.D. Martinez

The differential radar cross-section (RCS) of an RFID tag is an important parameter which determines the power of the modulated backscattered tag signal. The vector differential RCS of an RFID tag as seen by the reader is analysed and, for the first time, compared with experimental results in UHF band.

Introduction: Radio frequency identification (RFID) can be traced back to the late 1940's work on using RF modulated backscatter for communications [1]. Fig. 1 illustrates the operation of a modern passive RFID system which includes an RFID reader and an RFID tag, composed of an antenna and an integrated circuit chip. The reader signal alternates between a continuous wave (CW) and modulated transmissions. The tag sends data during one of the CW periods by switching its input impedance between two states, effectively changing its radar cross-section (RCS) and thus modulating the backscattered field. While the general theory of scattering from loaded antennas [2–5] and modulated probes [6] has been well established, and scalar RCS of RFID tags has also been recently analysed [7], such an important tag parameter as vector differential RCS has not been explicitly discussed in RFID literature and compared with experiment. If the receiver is non-coherent, it can only register a magnitude difference between two scalar RCS values (scalar differential RCS). If the receiver is coherent (such as an RFID reader where transmitter and receiver are phase locked), it detects both amplitude and phase of the signal and hence can register a vector difference between two RCS values (vector differential RCS). This difference depends on relative phases of the field scattered in different chip impedance states and is not a mere difference of two scalar RCS values. Two chip impedances may result in the same scalar RCS values for the tag but produce nonzero modulated backscattered power.

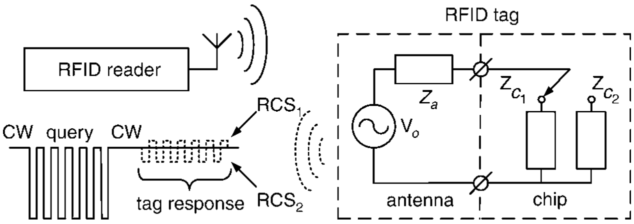

Fig. 1 *Passive RFID system and tag equivalent circuit*

Theory: The field scattered back from a loaded antenna (such as an RFID tag) can be divided into load-dependent and load-independent components which can be defined in several ways; e.g. the load-independent component can be associated with scattering from the open-circuited antenna (and the load-dependent component can be associated with the re-radiated power [4]). For minimum scattering antennas this power can be found from the antenna equivalent Thevenin circuit [2] shown in Fig. 1 (where $Z_a = R_a + jX_a$ is the complex antenna impedance, and Z_{c1} and Z_{c2} are the two values of complex RFID chip impedance). The scalar RCS is given by [5]:

$$\sigma = \frac{\lambda^2 G^2 R_a^2}{\pi |Z_a + Z_{c1,2}|^2} \tag{1}$$

where λ is the wavelength and G is the tag antenna gain. Since the scattered field is proportional to the complex current in the antenna, the differential backscattered power $P_{dif \cdot bs.}$ can be found as power re-radiated by the antenna driven by difference of complex currents I_1 and I_2 in different switched chip impedance states Z_{c1} and Z_{c2}:

$$P_{dif \cdot bs} = \frac{1}{2}|I_1 - I_2|^2 R_a G \tag{2}$$

Currents I_1 and I_2 can be found as

$$I_{1,2} = \frac{V_o}{(Z_a + Z_{c1,2})} = \frac{V_o}{2R_a}(1 - \rho_{1,2}) \tag{3}$$

where ρ_1 and ρ_2 are complex power wave reflection coefficients [8]:

$$\rho = \frac{Z_{c1,2} - Z_a^*}{Z_{c1,2} + Z_a} \tag{4}$$

and V_o is the antenna voltage on antenna terminals related to the power density S of an incoming wave as:

$$\frac{|V_o|^2}{8R_a} = S\frac{\lambda^2}{4\pi}G \tag{5}$$

After substituting (5), (4) and (3) into (2), we obtain the following expression for the magnitude of vector differential tag RCS:

$$\Delta\sigma = \frac{P_{dif \cdot bs.}}{S} = \frac{\lambda^2 G^2}{4\pi}|\rho_1 - \rho_2|^2 \tag{6}$$

Since the load-independent part is cancelled out, (6) is not limited to the minimum scattering case and is valid for arbitrary antennas (such as reflectors). Table 1 gives values of $\overline{\Delta\sigma}$ (which is differential RCS $\Delta\sigma$ normalised by $\lambda^2 G^2/4\pi$) for several cases of chip load impedances.

Table 1: Normalised RCS for different antenna load impedances

Z_{c1}	Z_{c2}	ρ_1	ρ_2	$\overline{\Delta\sigma}$
0	∞	−1	1	4
Z_a^*	0	0	−1	1
∞	Z_a^*	1	0	1

Complex reflection coefficients ρ_1 and ρ_2 can be plotted on a modified Smith chart, as shown in Fig. 2. The Smith chart is normalised to R_a, the contours of constant reactance correspond to modified reactance $X_{c1,2} + X_a$, and the origin corresponds to a perfect complex conjugate match between the chip and the antenna. Normalised vector differential RCS $\overline{\Delta\sigma}$ can be easily found as a square of the distance between the two mapped impedance points. For minimum scattering tag antennas, the difference between vector magnitudes $|\rho_1|$ and $|\rho_2|$ can be interpreted as normalised scalar differential RCS.

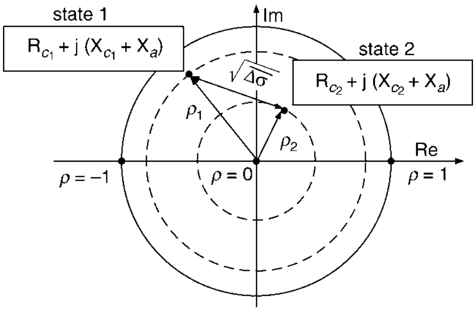

Fig. 2 *Smith chart representation of normalised differential RCS*

The magnitude and phase of the signal received from the tag in each state depend on several factors such as propagation environment, phase shifts of various RF system components, etc. The differential signal power is directly related to vector differential tag RCS which can be expressed using classical radar equation [9] as

$$\Delta\sigma = \frac{P_{received}}{P_t G_t^2}\frac{(4\pi)^3 d^4}{\lambda^2} \tag{7}$$

where $P_{received}$ is the power of the received modulated tag signal, P_t is the power transmitted by the reader, G_t is the gain of the reader transmit/receive antenna, and d is the distance to the tag.

Experimental results: The experimental setup is shown in Fig. 3. The measurement equipment was built on a National Instruments PXI modular hardware platform and included a PXI-5671 RF signal generator, a PXI-5660 RF signal analyser, a PXI-8196 LabVIEW controller, and a circulator. The tag was located inside a compact anechoic chamber at the distance of approximately 0.5 m away from the linearly polarised transmitting antenna with 6 dBi gain, approximating the far-field, free-space case. The signal generator output power was set to 15 dBm (minimum necessary to activate the tag in the 870–930 MHz frequency band). The LabVIEW application generated and sent commands to the RFID tag at different frequencies and calculated the power of the received modulated tag response. We used the RFID tag shown in Fig. 4 in the form of a small meandered dipole etched in 0.5 oz copper on a 2 mil polyester substrate with a dielectric permittivity of 3.5. The ISO 18000-6B RFID chip was mounted directly on antenna terminals using flip-chip packaging. The tag was similar to the one described in [10].

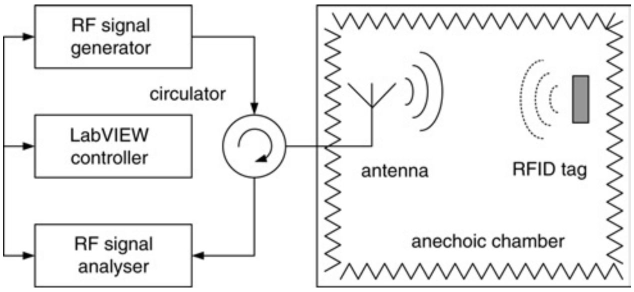

Fig. 3 *Experimental setup for measuring RFID tag differential RCS*

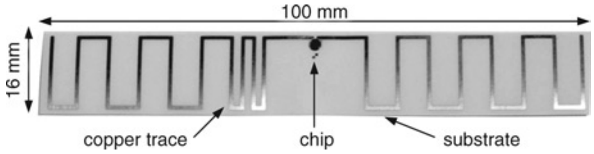

Fig. 4 *RFID tag used in measurements*

Fig. 5 shows theoretical and measured differential RCS values. Theoretical $\Delta\sigma$ was calculated from (6) where the tag antenna impedance and gain were obtained from electromagnetic simulations with Ansoft Designer. The RFID tag resonated in free-space at the frequency of approximately 900 MHz where the antenna gain was 1.8 dBi and the antenna impedance was $70 + j400\,\Omega$. The chip impedance was measured to be 12-j420 Ω at 900 MHz in the unmodulated state and was assumed to be close to 0 Ω in the modulated state. Experimental $\Delta\sigma$ was calculated from (7) where the received power was obtained from the RMS AC voltage of the tag response. The peak measured $\Delta\sigma$ at 900 MHz was −26 dBsqm (0.0025 m^2) which agreed well with the theoretical value of −27 dBsqm (0.002 m^2). The observed differences across the band are most likely due to insufficient information about the chip impedance in the modulated state which is difficult to measure directly. Because chip impedance depends on absorbed power, in a realistic scenario the differential tag RCS may vary with the distance between the tag and the reader.

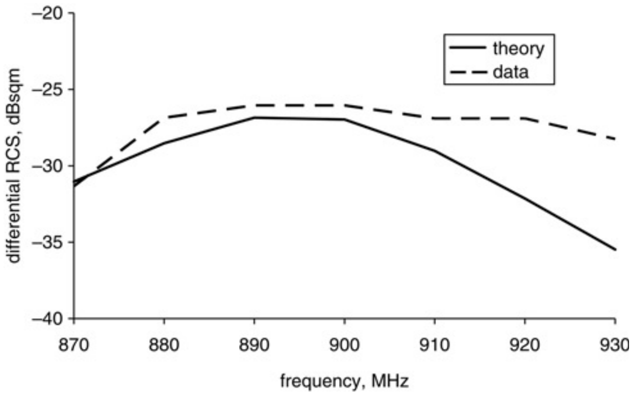

Fig. 5 *Theoretical and measured values of RFID tag differential RCS*

Conclusion: The differential RCS of an RFID tag is an important parameter which determines the power of the modulated backscattered signal. We have presented both theoretical and experimental results for the vector differential RCS of a UHF RFID tag which agree well and demonstrate the validity of the theory. We hope that these results will be useful to the wider RFID engineering community.

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