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CHIP IMPEDANCE MATCHING FOR UHF RFID TAG ANTENNA DESIGN

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Abstract—Passive UHF RFID tag consists of a microchip attached directly to an antenna. Proper impedance match between the antenna and the chip is crucial in RFID tag design. It directly influences RFID system performance characteristics such as the range of a tag. It is known that an RFID microchip is a nonlinear load whose complex impedance in each state varies with the frequency and the input power. This paper illustrates a proper calculation of the tag power reflection coefficient for maximum power transfer by taking into account of the changing chip impedance versus frequency.

1. INTRODUCTION

Passive radio frequency identification (RFID) is an automatic wireless data collection technology where RFID reader transmits a modulated RF signal to the RFID tag which consists of an antenna and an integrated circuit chip. The chip receives power from the antenna and responds by varying its input impedance and thus modulating the backscattered signal with data. Important RFID tag characteristics are maximum range and orientation sensitivity. In order to achieve optimum operating condition, the antenna impedance should be matched correctly to the chip impedance that is known to change with the received power on the chip as well as with frequency. When both chip impedance and antenna impedance are complex, calculating an accurate power reflection coefficient for tag antenna design is a challenging process.

Conventionally, chip vendor supplied constant values of chip impedances for the three center frequencies that correspond to the primary regional frequencies of operation: Europe (866.5 MHz), North America (915 MHz), and Asia (953 MHz). Using constant chip impedance value is not accurate for proper antenna design and tuning. This can be seen from a simple simulation using HFSS software package presented in this paper.

This paper starts off with the overview of RFID system with the introduction of Friis formula. It is then follows by a proper calculation of the power reflection coefficient taking into consideration the chip impedance variations. The chip impedance variation is measured by network analyzer at various power levels with respect to frequency. Next, a commercial tag (Avery Dennison AD-220) [1] was simulated using HFSS software package [2] and the numerical data are manipulated using custom Matlab codes to calculate the correct S-parameters of the tags. Theoretical maximum read range of the tag is then calculated and then comparison with the measurement result obtained from the Voyantic Tagformance RFID performance measurement instrument [3] is performed. This paper verifies that the calculated power reflection coefficient with varying chip impedance has better agreement in the simulation and measurement than single frequency chip impedance matching.

2. RFID SYSTEM OVERVIEW WITH ANTENNA EQUATIONS

The Communication in passive UHF RFID systems is based on backscattering: the reader transmits energy, commands and data to tag which then responds by backscattering its identification data back to the reader as depicted in Fig. 1. RFID Tags consist of an antenna and a microchip and the tags get all the energy for functioning from the electromagnetic radiation emitted by the reader through a rectifier, a voltage multiplier and a voltage modulator inside the microchip. The tag sends the information back to the reader by switching between two states: One is matched to the antenna and another one is strongly mismatched.

Shown in Fig. 2 is an example of signals received by the RFID reader antenna showing both forward and backward communications. RFID normally uses simple modulations such as ASK (Amplitude Shift Keying), PSK (Phase Shift Keying), and FSK (Frequency Shift

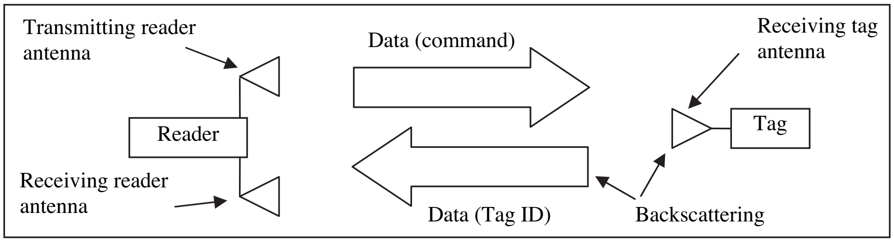

Figure 1. Passive RFID system.

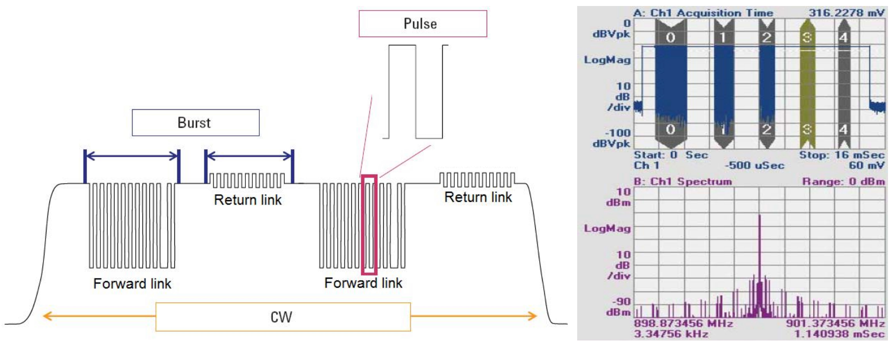

Figure 2. Reader received signals from Agilent vector signal analyzer.

Keying). Pulse refers to a single pair of encoded symbols, where the RF envelope goes low-high-low or high-low-high. Burst refers to contiguous set of encoded symbols from a single transmitter while CW is the entire signal from where the interrogator power turns on until it turns off [4].

The RF forward communication can be represented by one transmitting antenna and one receiving antenna as shown in Fig. 3. The power density at distance R_1 from the transmitting antenna in the direction $(\theta_{trans}, \phi_{trans})$ is

$$W_{trans} = \frac{P_{trans} G_{trans}(\theta_{trans}, \phi_{trans})}{4\pi R_1^2} \tag{1}$$

where P_{trans} is the input power of the transmitting antenna, and G_{trans} is the gain of the transmitting reader antenna. The $P_{trans}G_{trans}$ is called the reader transmitted equivalent isotropic radiated power (EIRP). The power received by the RFID tag antenna is expressed by

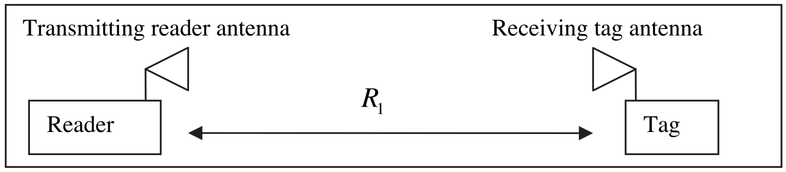

Figure 3. Reader to chip RF forward link.

the following antenna formula:

$$P_{tag} = W_{trans} G_{tag} \left(\theta_{tag}, \phi_{tag}\right) \frac{\lambda^2}{4\pi} \left|\hat{\rho}_{trans} \cdot \hat{\rho}_{tag}\right|^2 \tag{2}$$

where $G_{tag}(\theta_{tag}, \phi_{tag})$ is the gain of the tag receiving antenna in the direction $(\theta_{tag}, \phi_{tag})$, λ is the wavelength, and $|\hat{\rho}_{trans} \cdot \hat{\rho}_{tag}|^2$ is the polarization loss factor. Typical polarization loss factor for a dipole type of RFID tag and circularly polarized reader antenna is 0.5. Note that antenna gain is a function of direction and orientation, and it excludes the losses arising from impedance mismatches and polarization mismatches in accordance to IEEE standards. The power received by the RFID microchip due to the impedance mismatch between the tag antenna and the microchip is

$$P_{chip} = T_{tag} P_{tag} = \left(1 - |\Gamma_{tag}|^2\right) \times P_{tag} \tag{3}$$

where T_{tag} is the power transmission coefficient while $|\Gamma_{tag}|^2$ is the power reflection coefficient of the receiving tag antenna.

RFID readers typically come with separate transmitting and receiving antennas for maximum efficiency [9]. The backward communication is done by the backscattering of the signal off the tag antenna to be picked up by the reader receiving antenna as shown in Fig. 4. Thus the received power by the receiving reader antenna can be expressed as:

$$P_{rec} = W_{trans} \sigma_{tag} G_{rec} \left(\theta_{rec}, \phi_{rec}\right) \left(\frac{\lambda}{4\pi R_2}\right)^2 \left|\hat{\rho}_{scat} \cdot \hat{\rho}_{rec}\right|^2 \tag{4}$$

where G_{rec} is the gain of the receiving reader antenna in the direction of $(\theta_{rec}, \phi_{rec})$ directed to the tag, while $|\hat{\rho}_{scat} \cdot \hat{\rho}_{rec}|^2$ is the polarization efficiency with $\hat{\rho}_{scat}$ and $\hat{\rho}_{rec}$ are the polarization unit vectors of the scattered waves by the tag and receiving antenna. Distance between the tag and the receiving reader antenna is R_2 while σ_{tag} is the radar cross-section (RCS) of the tag which can be approximated by [5]

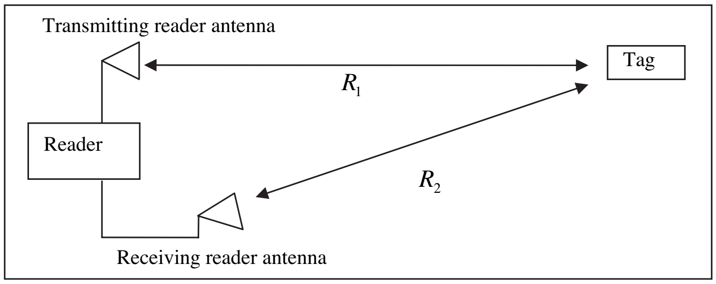

Figure 4. Chip to reader RF backscattered link.

$$\sigma_{tag} \approx \frac{4A_e R_a^2 G_{tag}(\theta_{rec},\phi_{rec})}{|Z_a+Z_c|^2} \approx \frac{\lambda^2 R_a^2 G_{tag}(\theta_{tag},\phi_{tag})\, G_{tag}(\theta_{rec},\phi_{rec})}{\pi|Z_a+Z_c|^2} \approx \frac{\lambda^2 R_a^2 G^2}{\pi|Z_a+Z_c|^2} \tag{5}$$

where A_e is the effective area of the RFID tag antenna, and λ is the wavelength of the carrier frequency. The resistance of the antenna with impedance Z_a is R_a while the microchip impedance is Z_c. For the purpose of backscattering return link, Z_c switches between two values representing the two modulation states. Therefore, two distinct RCS values are generated [12]. The difference between the two RCS values is:

$$\Delta\sigma_{tag} = |\sigma_1 - \sigma_2|\,. \tag{6}$$

Correspondingly, two distinct received powers will be picked up by the receiving reader antenna. The minimum detectable variation of the received power, ΔP_{rec} is called the sensitivity of the reader, $\Delta P_{rec\_\min}$. Rearranging Equations (1) to (3) we have the distance from the reader transmitting antenna to the tag expressed as follows:

$$R_1 = \left(\frac{\lambda}{4\pi}\right)\sqrt{P_{trans}G_{trans}(\theta_{trans},\phi_{trans})}\sqrt{\frac{G_{tag}(\theta_{tag},\phi_{tag})\,T_{tag}}{P_{chip}}\,|\hat{\rho}_{trans}\cdot\hat{\rho}_{tag}|^2}. \tag{7}$$

Similarly, rearranging Equations (1) and (4) with delta RCS we obtain the distance from the tag to the reader receiving antenna as follows:

$$R_2 = \left(\frac{\lambda}{4\pi R_1}\right)\sqrt{\frac{P_{trans}G_{trans}(\theta_{trans},\phi_{trans})\,G_{rec}(\theta_{rec},\phi_{rec})}{4\pi\,\Delta P_{rec}}}\sqrt{\Delta\sigma_{tag}\,|\hat{\rho}_{scat}\cdot\hat{\rho}_{rec}|^2}. \tag{8}$$

From the RFID tag antenna designer point of view, Equation (7) indicates that the maximum distance R_1 is constrained by the minimum power required for the operation of the tag microchip, P_{th}, or so called the threshold power of the RFID chip:

$$P_{chip}(R_1) \geq P_{th} \qquad P_{chip}(R_{1\max}) = P_{th}. \tag{9}$$

Equation (8) shows that maximum distance R_2 is constrained by the sensitivity of the reader $\Delta P_{rec\_\min}$:

$$\Delta P_{rec}(R_1, R_2) \geq \Delta P_{rec\_\min}. \tag{10}$$

Typical RFID measurement chamber has a monostatic setup. The maximum reading distance measurable by such a setup will provide a single value of maximum tag read range of $R_{\max}$. This read range is the lesser distance of the two maximum obtainable distances of R_1 and R_2 for the reason that RFID system depends on both the forward and backward communications. When the tag has received enough power to turn on, it might fail to reflect enough power to be detectable by the reader. However, the sensitivity of the reader receiving system is always very high (−70 dBm to −90 dBm) while the threshold power of UHF chip is only about −10 dBm. Assuming the tag antenna is matched properly to the chip, maximum obtainable $R_{2\max}$ will be a lot larger than $R_{1\max}$, thus making sensitivity of the reader not being a constraint. It is also known that the performance of the system degrade in the multiple readers and dense reader environment. The studies of reader to reader interference can be found under the paper by Kim et al. [10].

3. RFID TAG ANTENNA IMPEDANCE MATCHING

The goal of tag antenna designer is to design an antenna that could increase the maximum detection range of the RFID system. However, looking back at those equations mentioned in the previous section, there are not many antenna parameters that one could use to improve the performance of the tag antenna. RFID tag antenna gain is typically a small dipole antenna of about 2 dBi and there is not much flexibility to improve it any further without losing the omni-directional property of the antenna. As a result, design of a good tag antenna comes down to the enhancement of the reflection coefficient Γ_{tag}, which is to get a good matching for the antenna impedance to the chip impedance. The reflection coefficient matching complex antenna to the complex chip impedance is given by [6]

$$\Gamma = \frac{Z_c - Z_a^*}{Z_c + Z_a}. \tag{11}$$

The power reflection coefficient is then $|\Gamma|^2$. For a passive chip, the power reflection coefficient is always smaller than unity.

The graphical approach of calculating the reflection coefficient for RFID complex matching using Smith chart is recently determined by Nikitin [7] with reference to Kurokawas original paper [8]. For maximum power transfer matching, the rule of thumb is to employ the complex conjugate matching, thus the antenna input impedance should be equal to the complex conjugate of the chip impedance. However, the impedance of the microchip is not a constant value and it is a function of both frequency and the received power by the chip. This can be seen from the measured values of the input impedance plot of Impinj Monza chip versus frequency at various sensitivity levels as shown in Fig. 5. The antenna should be conjugate matched to the minimum operational power chip impedance to maximize the tag read range. The minimum operating power of the chip defined by the chip manufacturer is -11 dBm while the measurement of the chip impedance was stopped at -6 dBm. Therefore nonlinear extrapolation of the chip impedance was needed for the minimum operating level -11 dBm at all frequencies. The extrapolation was done using polynomial interpolation. The extrapolation of the chip resistance extends below zero at -11 dBm for every frequency. Subsequently a data point of zero ohm at negative infinity dBm of power was added to correct the approximation. The matching should be done using the chip impedance curve at the minimum received power level.

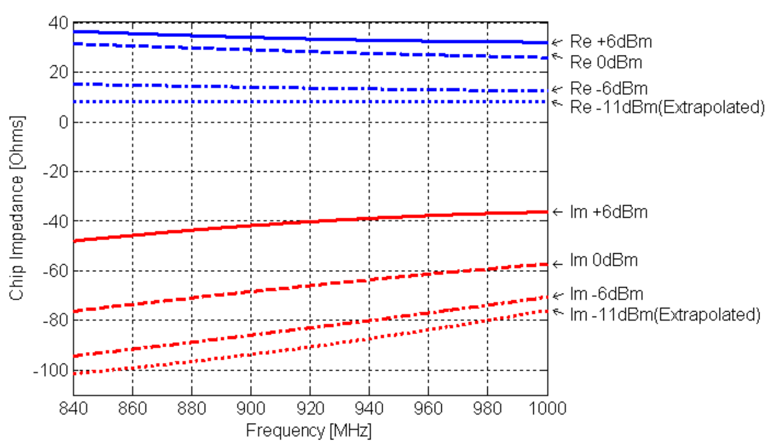

Figure 5. Input impedance of Impinj Monza chip with respect to different received power levels.

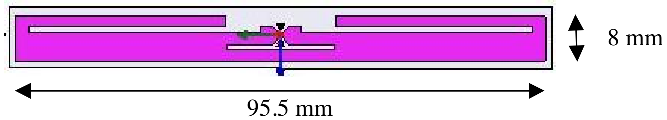

Figure 6. Image of the simulated Avery Dennison AD-220 RFID tag using HFSS.

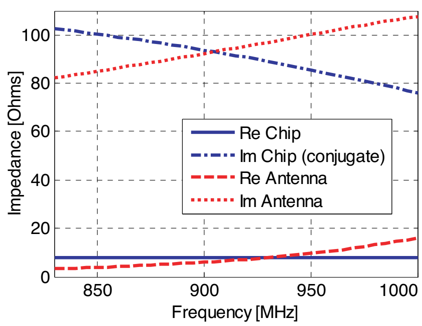

Figure 7. Simulated antenna impedance along with the conjugate of the chip impedance at −11 dBm.

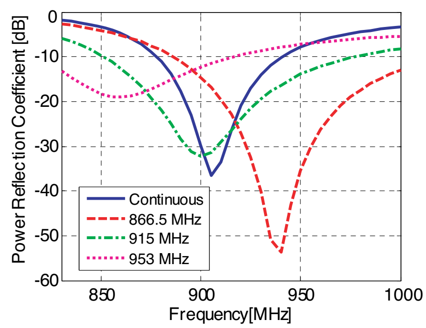

Figure 8. The AD-220 tag power reflection coefficient $|\Gamma|^2$ versus frequency.

4. COMPARISON OF SIMULATION AND MEASUREMENT

Figure 6 shows a simulation of a commercial AD-220 (Avery Dennison) RFID tag. This antenna is a printed antenna of T-matched folded dipole structure. The simulated antenna impedance is plotted side by side with the conjugated chip impedance in Fig. 7. Figure 8 shows the incorrect power reflection coefficients calculated using the constant chip impedance values at various frequencies as well as the correct power reflection coefficient calculated using the continuous changing chip impedance. The correct power reflection coefficient has a smaller bandwidth than the incorrect power reflection coefficients. This AD-220 tag was designed for North America operation in the frequency range of 902 MHz–928 MHz. It is a silver ink of (7 microns ink thickness) printed tag on Polyethylene Terephthalate (PET) substrate (3 mils) of permittivity 2.8. The structure is simulated with the tag residing on top of a 4 mils thick plastic of permittivity 2.8 just like how the experiment measurement was conducted. The conductivity of silver ink is assumed to have 10% conductivity of silver. At least 14 passes were needed for the imaginary part of the antenna impedance to converge to 0.5 degrees in this simulation.

Performance measurement of the tag was conducted in the RFID anechoic chamber at The University of Mississippi using the Voyantic Tagformance Lite RFID measurement system. Figure 9 compares the experimentally collected maximum read range with the theoretically calculated maximum read range using the three constant chip

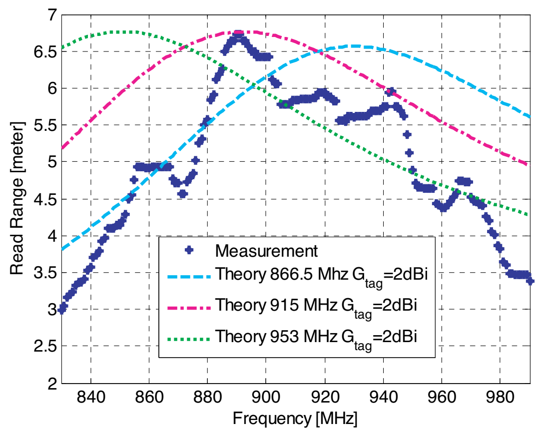

Figure 9. Experimental and theoretical read ranges for the three fixed chip impedances.

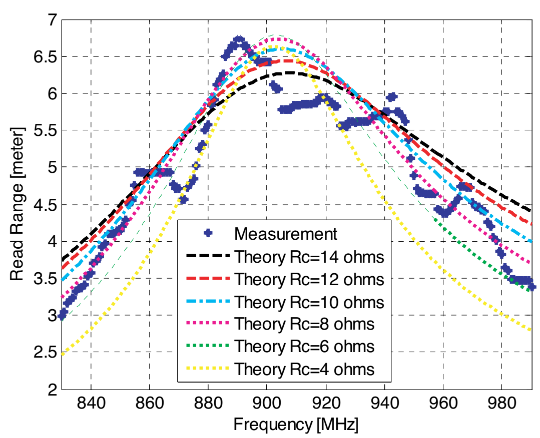

Figure 10. Experimental and theoretical read ranges for different assumed chip resistances.

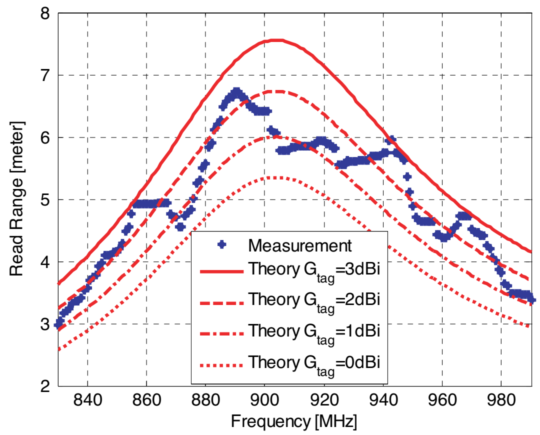

Figure 11. Theoretical and experimental read ranges for different assumed tag antenna gain values.

impedances of the three regional frequencies. It is assumed that the chip is operating at the minimum power of −11 dbm at maximum read range. The maximum allowable EIRP by the Federal Communications Commission (FCC) is 36 dBm. However, EIRP of 35 dBm is the limit design engineer uses. The impedance at 866.5 MHz (8-j98Ω) shows good agreement at the lower frequency range, while 915 MHz (8-j91Ω) matching and 953 MHz (8-j85Ω) matching show good agreement at their corresponding higher frequency range. However, none of them have good agreement with measurements for the entire range of frequency. The matching of the continuously changing chip reactance covering the frequency range of 830 to 990 MHz is shown in Fig. 10 with several constant chip resistances. The reactance of the chip is specified by the extrapolated curve for −11 dBm shown in Fig. 5, while the resistance is kept constant with frequency. Several values of the chip resistance were assumed, and it was found that the chip resistance of 8 ohms was the best fit to the measurement for a 2 dBi Gain tag antenna. Figure 11 is the plots of the theoretical read range of different tag antenna gain using frequency dependent chip impedance.

5. CONCLUSION

The maximum read range is an important parameter for RFID tag designs. Based on the backscattering theory, this paper derives a series of equations through which the maximum read range can be computed from the tag antenna impedance obtained from commercial

EM software such as HFSS. In particular, the complex impedance matching and the frequency dependent chip impedance are highlighted in the computation. The computed maximum read range results agree well with the measured data. This paper provides guidelines for future RFID tag antenna design.

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