

Power Reflection Coefficient Analysis for Complex Impedances in RFID Tag Design

Pavel V. Nikitin, *Member, IEEE*, K. V. Seshagiri Rao, *Senior Member, IEEE*, Sander F. Lam, Vijay Pillai, *Member, IEEE*, Rene Martinez, and Harley Heinrich

Abstract—Kurokawa's method of calculating the power reflection coefficient from the Smith chart in the situation when one complex impedance is directly connected to another is applied to passive RFID tag design, where power reflection is important, as it determines the tag characteristics. The performance analysis of a specific RFID tag is presented together with experimental data, which is in close agreement with the theory.

Index Terms—Antennas, integrated circuits (ICs), power reflection, RF identification (RFID).

I. INTRODUCTION

RF identification (RFID) is a rapidly developing technology [1]. A typical back-scattered RFID tag consists of an antenna and a chip [2]. The chip is usually placed right at the terminals of the tag antenna, and both the chip and antenna have complex input impedances. For years, antennas have been designed primarily to match either 50- or 75- Ω loads. However, RFID tag antennas must be directly matched to the chip complex impedance to maximize tag performance (adding an external matching network is usually prohibitive due to cost and fabrication issues).

A very useful impedance matching tool for any microwave engineer is the Smith chart. It was developed by Smith in the 1930s [3] and is the most widely known graphical impedance chart. The Smith chart is typically normalized to a real impedance and can be used to find a lossless transmission-line section for desired impedance matching between two complex impedances [4]. Kurokawa [5] proposed a method where a modified impedance function is mapped onto the conventional Smith chart to determine a power reflection coefficient in the case when both generator and load impedances are complex, but no lossless transmission line is present between them.

Such a case is typical in passive RFID tags, where the minimum power reflection coefficient between the antenna and chip is desired. In this paper, the method of the power reflection coefficient proposed by Kurokawa is applied to RFID tag design. We also present measurement data, which are in good agreement with theory.

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The authors are with the Intermec Technologies Corporation, Everett, WA 98203 USA (e-mail: pavel.nikitin@intermec.com; kvs.rao@intermec.com; sander.lam@intermec.com; vijay.pillai@intermec.com; rene.martinez@intermec.com; harley.heinrich@intermec.com).

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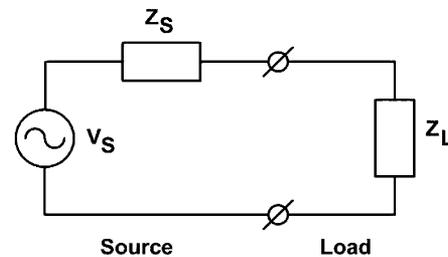


Fig. 1. Generator-load circuit with two complex impedances.

II. POWER REFLECTION-COEFFICIENT METHOD

Consider a one-port network, shown in Fig. 1, which represents a generator-load circuit with complex source and load impedances.

Kurokawa [5] described a concept of power waves traveling between the generator and load and introduced the following definitions for the power wave reflection coefficient s :

$$s = \frac{Z_L - Z_S^*}{Z_L + Z_S} \quad (1)$$

and the power reflection coefficient $|s|^2$

$$|s|^2 = \left| \frac{Z_L - Z_S^*}{Z_L + Z_S} \right|^2, \quad 0 \leq |s|^2 \leq 1. \quad (2)$$

The power reflection coefficient $|s|^2$ shows what fraction of the maximum power available from the generator is not delivered to the load.

Kurokawa also described a straightforward and graphically intuitive way of calculating the power reflection coefficient $|s|^2$ by observing that the power wave reflection coefficient s plotted on the Smith chart corresponds to the vector drawn to the point where the normalized impedance is

$$r + jy = \frac{R_L}{R_S} + j \frac{X_L + X_S}{R_S}. \quad (3)$$

This allows a designer to utilize a conventional Smith chart normalized to real impedance with the understanding that contours of constant reactance X_L are now to be interpreted as contours of constant modified reactance $X_L + X_S$, as shown in Fig. 2.

The contours of constant power $|s|^2$ are concentric circles centered around the origin of the Smith chart, which corresponds to a perfect complex conjugate match ($Z_L = Z_S^*$). When both R_L and R_S are real and positive, s lies within a unit

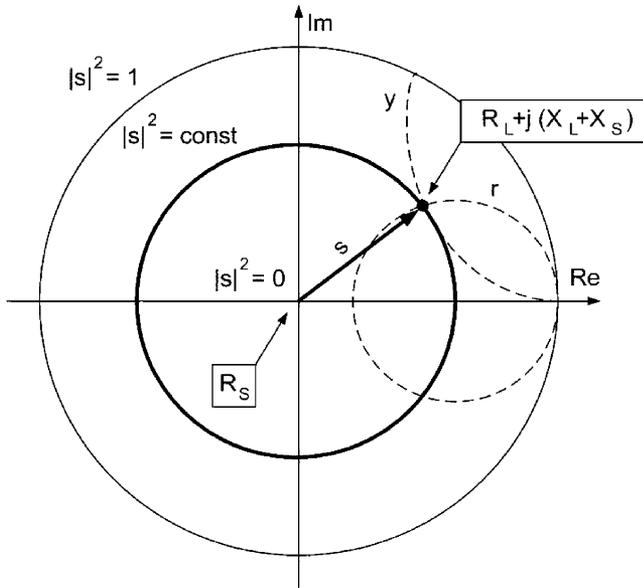


Fig. 2. Complex power wave reflection coefficient s mapped onto the Smith chart normalized to R_S .

circle, whose outer edge corresponds to a complete mismatch case ($|s|^2 = 1$).

The power reflection coefficient $|s|^2$ can be easily determined from the Smith chart as a square of the distance (measured as a fraction of the circle radius) between the origin and the mapped impedance point $R_L + j(X_L + X_S)$. Kurokawa's method is general and can be used for any microwave circuits with complex impedances.

III. RFID TAG DESIGN EXAMPLE

A. Read Range

Let us demonstrate how Kurokawa's method can be applied to analyze the performance of a passive RFID tag. The fact that passive RFID tags are powered solely by the incoming RF energy, combined with cost and fabrication requirements, imposes a unique set of criteria on RFID tag antenna design, including frequency bandwidth, directivity, size and form, sensitivity to different objects the tag is placed on, reliability, and, finally, tag read range.

Read range is an important characteristic of the RFID tag. It is the maximum distance from which the tag can be detected. One limitation on the range is the maximum distance from which the tag receives just enough power to turn on and scatter back. Another limitation is the maximum distance from which the reader can detect this scattered signal. The read range is the smaller of the two distances (typically, the first one since RFID reader sensitivity is usually high).

Theoretical read range r_{\max} depends on the power reflection coefficient and can be calculated using the Friis free-space formula as

$$r_{\max} = \frac{\lambda}{4\pi} \sqrt{\frac{P_t G_t G_r (1 - |s|^2)}{P_{\text{th}}}} \quad (4)$$



Fig. 3. Intermec UHF RFID tag.

where λ is the wavelength, P_t is the power transmitted by the RFID reader, G_t is the gain of the transmitting antenna ($P_t G_t$ is EIRP, equivalent isotropic radiated power), G_r is the gain of the receiving tag antenna, and P_{th} is the minimum threshold power necessary to power up the chip. Typically P_t , G_t , G_r , and P_{th} are slow varying, and $|s|^2$ is dominant in frequency dependence and primarily determines the tag resonance.

B. Tag Design

RFID tag antennas are typically designed for an application-specific integrated circuit (ASIC) (new integrated circuit (IC) design and manufacturing is a big and costly venture), thus, chip impedance is usually given to an antenna designer. When utilizing Kurokawa's method, we will look at power reflection between the chip and antenna with chip impedance fixed. A circuit shown in Fig. 1 represents the RFID tag in the receiving mode, where Z_L is the chip impedance, Z_S is the antenna impedance, and V_S is an open-circuit RF voltage developed on the terminals of the tag antenna.

As an example, consider a UHF RFID tag developed at the Intermec Technologies Corporation, Everett, WA [6]. This tag was designed for pallet-labeling applications in Europe to provide at least 2 m of range with 0.82-W transmitter EIRP (European standard for RFID) in the 2-MHz band around 869 MHz when placed into a 30-mm-thick rectangular foam container. These requirements resulted in the antenna whose geometry is shown in Fig. 3. The tag consists of an RFID chip connected to a copper antenna printed on an FR4 dielectric substrate, 190 mm \times 22 mm in size. The RFID chip is the Philips' EPC 1.19 ASIC in a TSSOP8 package with a threshold power $P_{\text{th}} = -10$ dBm and packaged chip-on-board impedance of $Z_L = 16 - j350 \Omega$, approximately constant in the frequency band of interest (860–960 MHz).

Due to size specifications, some type of dipole antenna was a natural choice. Since relatively high range was needed, loading bars were added to increase antenna gain and to control antenna resistance. An inductive stub was added to provide a better match for the chip capacitive impedance. The tag antenna was designed using Ansoft HFSS for antenna gain and impedance calculations.

Fig. 4 shows the frequency-dependent antenna impedance Z_s , calculated in the 860–960-MHz band with Ansoft HFSS, mapped using Kurokawa's representation given by (3) onto the Smith chart normalized to 16Ω (chip resistance).

Power reflection coefficient at the tag resonant frequency can be easily determined as $|s|^2 = 0.6^2 = 0.36$ (where 0.6 is the minimum distance between the origin and the impedance locus curve). The antenna impedance at this point can also be easily found from r and y coordinates as $Z_S = R_L(5 - j0.8) - jX_L = 80 + j363 \Omega$. The tag resonant frequency (where $|s|^2$ is minimum) is determined to be 900 MHz.

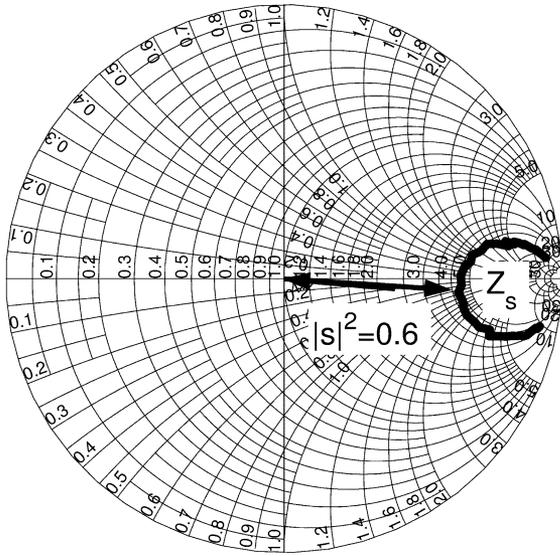


Fig. 4. Antenna impedance Z_S mapped onto the Smith chart normalized to 16Ω and a graphical method of determining the power reflection coefficient.

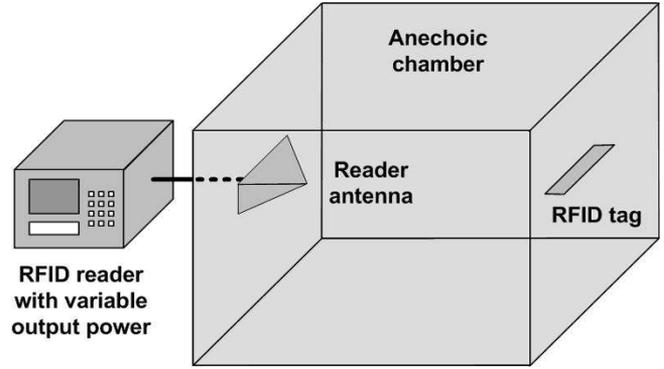


Fig. 6. RFID read-range measurement setup.

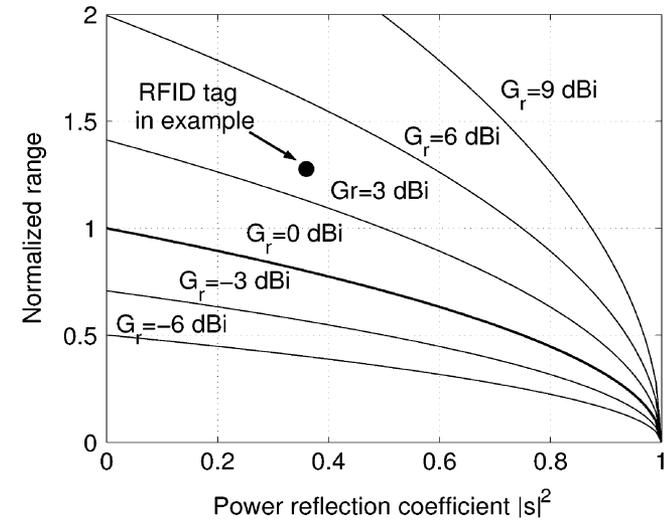


Fig. 5. Normalized read range versus power reflection coefficient for different tag antenna gain values (frequency is 900 MHz, normalization constant is 2.4 m, calculated for $P_{th} = -10$ dBm and $EIRP = 0.82$ W).

For the given frequency f , chip sensitivity P_{th} , and RFID reader EIRP, (4) can be normalized to the range of the tag with $G_r = 0$ -dBi antenna perfectly matched to the complex conjugate chip impedance ($|s|^2 = 0$). Such normalization allows the read range to be plotted as a function of the power reflection coefficient for different tag antenna gain values, as shown in Fig. 5 (where the frequency is 900 MHz and the normalization constant is 2.4 m, calculated for chip sensitivity $P_{th} = -10$ dBm and transmitter with $EIRP = 0.82$ -W transmitter).

Our example RFID tag, which has $G_r = 4.1$ dBi and $\rho = 0.36$, is represented as a point in Fig. 5. Tag range can be further increased by either increasing the gain of the antenna and/or improving the impedance match. The RFID tag design process involves inevitable tradeoffs between antenna gain, impedance, and bandwidth. The normalized chart shown in Fig. 5 helps the

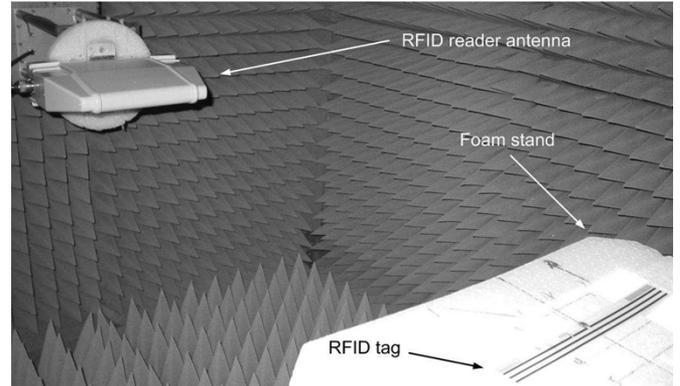


Fig. 7. Tag range measurement chamber.

designer to estimate the range tradeoff between the impedance matching and gain.

C. Comparison to Experimental Results

The tag read range was measured using the setup shown in Fig. 6. An RFID reader with the variable power output was connected to the transmitting antenna with gain G_t using the cable with loss L_c . The tag was placed at a fixed distance d from the reader antenna in an anechoic chamber and oriented in the direction of maximum gain. At each frequency, the minimum power P_{min} required to communicate with the tag was recorded.

Since the gain of the transmitting antenna, the cable loss, and the separation distance are known ($G_t = 6.3$ dBi, $L_c = -0.5$ dB, and $d = 0.9$ m), the tag read range for any desired value of EIRP can be determined as

$$r_{max} = d \sqrt{\frac{EIRP}{P_{min} G_t L_c}}. \quad (5)$$

Maximum allowed value of EIRP used in any particular RFID system implementation is determined by local country regulations. Fig. 7 shows the inside view of the anechoic chamber used at the Intermec Technologies Corporation for tag range measurement.

Fig. 8 displays the measured range (from (5) for $EIRP = 0.82$ W) and the theoretical range [from (4)]. When the tag is placed in a container on a pallet, its resonant frequency shifts down to 869 MHz and the range becomes 2.2 m.

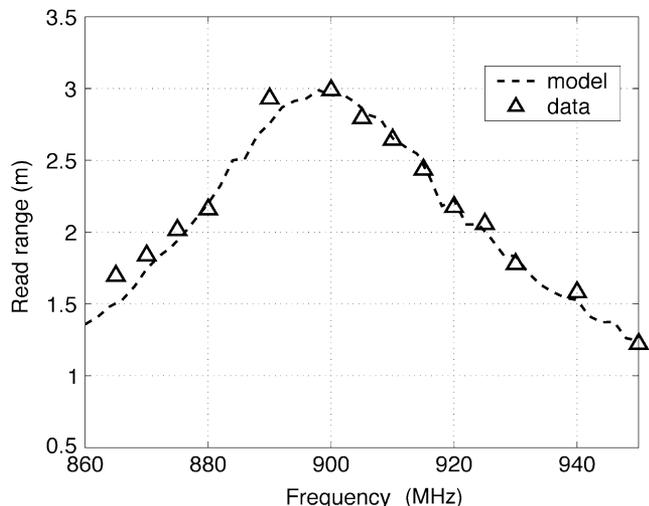


Fig. 8. Theoretical and experimental read ranges for RFID tag shown in Fig. 3 (EIRP = 0.82 W).

It can be seen that theoretical and experimental curves for the tag range are in close agreement, which demonstrates the accuracy of the antenna model and validity of (4). The read range reaches a maximum at 900 MHz, where the power reflection coefficient is minimal. This agrees with the frequency determined from the Smith chart analysis of the power reflection coefficient.

IV. CONCLUSION

In this paper, we have applied Kurokawa's power reflection coefficient method to passive RFID tag design where an antenna and chip with complex impedances are directly connected to each other. We have described the design process for a specific RFID tag and have demonstrated good agreement between experimental measurements and theory.

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Pavel V. Nikitin (S'98-M'02) received the B.S. and M.S. degrees in electrical engineering from Utah State University, Logan, UT, in 1994 and 1998, respectively, the B.S. degree in physics from Novosibirsk State University, Novosibirsk, Russia, in 1995, and the Ph.D. degree in electrical and computer engineering from Carnegie-Mellon University, Pittsburgh, PA, in 2002.

In Summer 1999, he was a Software Design Engineer with the Ansoft Corporation, Pittsburgh, PA. In Summer 2000, he was a Design Development Engineer with the Microelectronics Division, IBM Corporation, Essex Junction, VT. In 2002, he joined the Department of Electrical Engineering, University of Washington, Seattle, as a Research Associate, where he was involved with computer-aided design of mixed-technology systems-on-chip. In 2004, he joined the Intermec Technologies Corporation, Everett, WA, where he is currently a Lead Engineer with the RFID Intellitag Engineering Department involved with the design and development of antennas for RFID tags. He has authored over 35 technical publications. He also has several patents pending.

Dr. Nikitin was the recipient of the ECE Teaching Assistant of the Year Award presented by Carnegie-Mellon University.



K. V. Seshagiri Rao (S'78-M'84-SM'91) received the Ph.D. degree from the Indian Institute of Technology, Kharagpur, India, in 1984.

In 1979, he joined the Indian Institute of Technology, as a Senior Research Assistant, and subsequently joined the faculty in 1984. Apart from his teaching at IIT, he has also participated in various projects in the area of antennas and circuits sponsored by defense and aerospace. In 1988, he was on sabbatical leave from IIT as a Research Associate with the University of Ottawa, Ottawa, ON, Canada. In 1993, he joined Antenna Research Associates, Beltsville, MD, where he was involved with the design and development of antennas. He then joined the T. J. Watson Research Center, IBM, Yorktown Heights, NY, as a Research Staff Member, where he was involved with RFID. In 1998, he joined the Intermec Technologies Corporation, Everett, WA, as one of the core team members with the RFID technologies acquired from IBM. He is currently a Staff Technologist with the RFID Intellitag Engineering Department, Intermec Technologies Corporation, where he also manages a small group in the area of RFID transponder design and development. He coauthored *Millimeter-Wave Microstrip and Printed Circuit Antennas* (Norwood, MA: Artech House, 1991). He has authored or coauthored approximately 35 technical publications in standard journals and conferences. He also has 13 U.S. patents in the area of RFID.



Sander F. Lam received the Bachelor of Engineering degree from McMaster University, Hamilton, ON, Canada, in 1981.

Since 1982, he has been involved with various RF communication hardware design. He was involved in the research and development of single-conversion TVRO and CATV headend equipment with Triple Crown Electronics Inc., Mississauga, ON, Canada. In 1989, he joined U.S.-based Auger Communication Products Inc., where he was the lead RF Designer involved with CATV two-way broad-band trunk distribution amplifiers. In 1997, he joined the Intermec Technologies Corporation, Everett, WA, where he is currently the Senior RF Engineer. His interests include various RF communication hardware design and RFID tag development.



Vijay Pillai (M'99) received the B.S. degree in electronics and communication from the Indian Institute of Technology, Madras, India, in 1997, and the M.S. degree in electrical engineering from Clemson University, Clemson, SC, in 1999.

He is currently a Principal Engineer with the Intermec Technologies Corporation, Everett, WA, where he develops next-generation RFID systems. He has been involved in one of the earliest globally accepted RFID chips for UHF and microwave bands. He led the development of chips based on the Global

Tag Initiative (Gtag), which was the first globally accepted RFID standard. His interests are low-power circuit design techniques for RFID, RF front-ends for passive tags, and microwave theory. He has authored four publications. He has approximately ten issued or pending patents.



Rene Martinez received the B.S. degree in electrical engineering from the University of Maryland at College Park, in 1987, and the Master of Engineering degree (with a specialization in analog-to-digital conversion) and Ph.D. degree in electrical engineering (with a specialization in RF circuits, antennas, and systems) from Cornell University, Ithaca, NY, in 1990 and 1994, respectively.

He was a Research Staff Member with IBM Research and as a Staff Scientist with Lawrence Berkeley Laboratories. He is currently a Chief

Technologist with the Intermec Technologies Corporation, Everett, WA, where he manages a team of engineers that have developed a full product line of RFID readers under Federal Communications Commission (FCC), European, and Japanese regulations. He has led the development team that obtained the first FCC Part 15 approval and the first European Telecommunications Standards Institute (ETSI) 302 208 certification for passive UHF RFID readers. He authored six IEEE publications during his graduate studies. He has given invited talks at Stanford University, AT&T Bell Laboratories, and the Massachusetts Institute of Technology (MIT). He currently holds patents in RFID, wireless communications, and RADAR.



Harley Heinrich received the Ph.D. degree from Stanford University, Stanford, CA.

He is currently the Chief Technologist for Intelitag RFID technology with the Intermec Technologies Corporation, Everett, WA. Prior to joining the Intermec Technologies Corporation, he was with the T. J. Watson Research Center, IBM, for ten years. In 1992, he was one of the original founders of the IBM RFID effort and led the development of the high-performance low-cost RFID tag package, antenna, and chip efforts. Prior to his affiliation with IBM, he

simultaneously worked on his doctoral dissertation in ultrafast microwave electrooptics and led chip design efforts with Hewlett-Packard as an Analog Integrated Circuit Designer. He has authored and presented over 30 technical papers. He holds 39 patents, many of which are both U.S. and international.

Dr. Heinrich was the co-chair of the EPCglobal Gen2 Working Group to develop the UHF Generation 2 Standard for RFID for use in consumer product group companies like Wal-Mart, Target, Procter & Gamble, and many other Fortune 500 companies. He was the recipient of the 2003 Ron Mahany Award for Outstanding Innovation for his work in RFID, which is the Intermec Technologies Corporation's highest honor. He and his group were the recipients of the Outstanding Invention Achievement Award, which recognizes the single most important individual and group contribution for IBM research for the year.