Limitations of Forward and Return Links in UHF RFID with Passive Tags

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Abstract**—Backscatter radio wireless communication by modulating signals scattered from a radio frequency transponder (RF tag) is fundamentally different from conventional radio because it involves two distinct links: the power-up (forward) link for powering the passive RF tags, and the backscatter (return) link for the describing backscatter communication. Because of severe power limitations on the RF tag such as chip sensitivity, antenna gain, antenna polarization and impedance match, a thorough knowledge of the backscatter channel is necessary to maximize backscatter-radio and radio-frequency identification (RFID) system performance. This paper examines the relative roles of the forward and reverse links in determining power received in tag, return power in reader, power ratio and the operational range of passive UHF RFID systems. It analysed the limitations imposed on the range performance of passive UHF RFID systems by such factors as tag characteristics, propagation environment, and RFID reader parameters.**

Keywords**— RFID, UHF RFID, passive tags, free space channel, limitations of forward and reverse links.**

I. INTRODUCTION

Radio frequency identification (RFID) is an automatic wireless data collection technology with long history of more than 50 years in the field of wireless communications, but only the last decade it has received a considerable attention for becoming a useful general purpose technology [1,2]. RFID is a technology that uses electromagnetic waves to identify object, animal or people in an unique manner [3]. In RFID systems, an item is tagged with a tiny silicon chip and an antenna; the chip plus antenna (together called a “tag”) can then be scanned by mobile or stationary readers using radio waves. The chip can be encoded with a unique identifier, allowing tagged items to be individually identified by a reader [2]. Primary components of RFID devices have three primary elements: a chip, an antenna, and a reader. A fourth important part of any RFID system is the database where information about tagged objects is stored [4]. The main criteria for readers include the following: operating frequency (LF, HF, UHF) readers, Protocol ability, networking to host capability [5], different regional regulations (e.g. UHF readers): UHF frequency agility 902 to 930 MHz in the United States and 869 MHz in Europe, and power regulations of 4W in the United States and 500 mW in some other countries [3]. There are two main types of RFID systems, passive and active RFID systems. In a passive RFID system operates in the following way, RFID reader transmits a modulated RF signal to the RFID tag consisting 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. In radio communications, the most critical obstacle is always received power. So in RFID systems, the power- up link or powering passive RF tags, and the backscatter link for describing backscatter communication are most important to be reliable radio links for successful object tracking. The relationship between the scattered signal received at the reader and the transmitted link to the tag is well understood in the free field. In this paper, the relationship between these links is analysed. The analyses, considers free-field models of the forward and reverse links with some discussion about which is the constraining link in an ideal system. Measurements of transmission and scatter links are presented to compare free space path- loss effects in an anechoic chamber. The paper is outlined as follows: principles of RFID is presented in Section II, far- field RFID propagation and backscatter principles are discussed in Section III, read/write range is given in Section IV and finally the conclusions are drawn in Section V.

II. RFID PRINCIPLES

A basic RFID system consists of a radio frequency tag (RF transponder) and a reader (interrogator). The reader sends out the RF signal carrying commands to the tag. Consequently, the tag responds with its stored data to be authorized, detected, or counted. The RFID devices may be divided into two main classes: active and passive. Active tags require a power source, they have ranges of greater than 100 meters [6] and high cost [7]. Passive RFID is of interest because the tags have no power source, they make use of the power received from the incoming RF signal to generate their own supply voltage, passive tags have ranges of less than 10 meters and they low cost [8]. A passive tag consists of three parts: an antenna, a semi-conductor chip attached to the antenna, and some forms of encapsulation. The tag antenna captures energy and transfers the tag's ID (the tag's chip coordinates this process). The encapsulation maintains the tag's integrity and protects the antenna and chip from environmental conditions or reagents [9]. Two fundamentally different RFID design approaches exist for transferring power from the reader to the tag: magnetic induction and electromagnetic (EM) wave capture. These two designs take advantage of the EM properties associated with an RF antenna—the near field and the far field [4].

III. FAR-FIELD RFID PROPAGATION AND BACKSCATTER PRINCIPLES

RFID systems based on UHF and higher frequencies use far-field communication and the physical property of backscattering or "reflected" power. Far-field communication is based on electric radio waves where the reader sends a continuous base signal frequency that is reflected back by the tag's antenna. During the process, the tag encodes the signal to be reflected with the information from the tag (the ID) using a technique called modulation (i.e., shifting the amplitude or phase of the waves returned) [10]. Most theoretical analyses, at least in the first approximation, assume the so-called free-space propagation. In this study *free space* simply means that there is no material or other physical phenomenon present except the phenomenon under consideration. Free space is considered the baseline state of the electromagnetic field. Radiant energy propagates through free space in the form of electromagnetic waves, such as radio waves and visible light (among other electromagnetic spectrum frequencies). In the wireless industry, most models and formulas used today are semi-empirical, that is, based on the well-known radio propagation laws but modified with certain factors and coefficients derived from field experience [11]. RFID is definitely an area where this practice is required; short distances cluttered with multiple tags and/or other objects are potential obstacles to radio propagation and will cause serious deviations, predictable or not, from the theoretical calculations [3]. RFID tags based on far-field emissions (see Fig. 1) capture EM waves propagating from a dipole antenna attached to the reader. A smaller dipole antenna in the tag receives this energy as an alternating potential difference that appears across the arms of the dipole. The technique designers use for commercial far-field RFID tags is *back scattering* [4]. Designing an antenna with precise dimensions, should be tuned to a particular frequency and absorb most of the energy that reaches it at that frequency. However, if an impedance mismatch occurs at this frequency, the antenna will reflect back some of the energy toward the reader which can then detect the energy using a sensitive radio receiver. By changing the antenna's impedance over time, the tag can reflect back more or less of the incoming signal in a pattern that encodes the tag's ID.

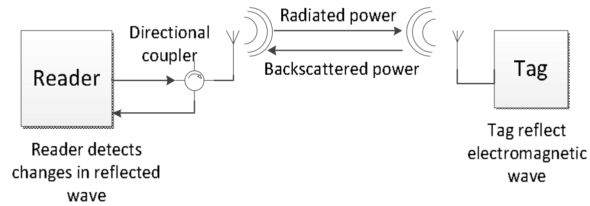

Fig. 1 Far-field power/communication mechanism for RFID tags

A backscatter tag operates by modulating the electronics connected to the antenna in order to control the reflection of incident electromagnetic energy. For successful reading of a passive tag, two physical requirements must be met:

1. ***Forward power transfer:*** sufficient power must be transferred into the tag to energize the circuitry inside. The power transferred will be proportional to the second power of the distance.

2. ***The radar equation:*** the reader must be able to detect and resolve the small fraction of energy returned to it. The power received will be reduced proportional to the fourth power of the distance. The symbols used in this paper for far-field system performance is outlined in Table 1. In real deployments, these parameters can vary with signal parameters, Doppler shift, tag damage or deterioration, and tag antenna detuning [12].

1. *Forward Power Transfer*

In forward link, the output power is

$$P_{EIRP} = P_{TR}\, G_R \qquad (1)$$

The typical maximum output power is 29dBm (500mW ERP, 825mW EIRP), 35dBm (2W ERP, 3.3W EIRP) and 36dBm (4W EIRP). The typical value of isotropic gain of reader antenna is assumed to be 6dBi. Therefore, the maximum output power from power amplifier should be 23dBm, 29dBmand 30dBm, respectively [4]. The power received at tag according path loss in free space can be expressed as

$$P_{REC,TAG} = P_{TR} G_R G e_{tag} e_{rd} e_{pol} \left(\frac{\lambda}{4\pi d}\right)^2 \qquad (2)$$

The power was arrived to the tag is function to the distance from the reader is illustrated in Fig. 2. as distance increases as power that received in tag decreases, and as the power that is transmitted from reader increases as the distance in which reader can read the target tag and the received power in tag increase. From the industrial experience, RF input power of 10uW (-20dBm) to 100uW (-10dBm) is required to power on tag [13]. Table 2 shows some values of received power in the tag to different transmit power and distances.

2. *The Radar Equation*

Radar principles tell us that the amount of energy reflected by an object is dependent on the reflective area of the object—

the larger the area, the greater the reflection. This property is referred to as the radar cross section (RCS) [13]. The RCS is an equivalent area from which energy is collected by the target and retransmitted (backscattered) back to the source. For an RFID system in which the tag changes its reflectivity in order to convey its stored identity and data to the reader, this is referred to as differential radar cross section or ΔRCS (σ).

TABLE I
LINKS SYMBOLS

Meaning	**Terms**	**Meaning**	**Terms**
The Effective Isotropic Radiated Power (EIRP) of the reader	P_{EIRP}	Gain of tag antenna	G
Gain of reader antenna	G_R	Radar cross section	σ
Power transmitted from reader	P_{TR}	Received power density of the reader	S_{REC}
The power received at tag and reader	$P_{REC,TAG}$, $P_{REC,READ}$	The minimum threshold power required to power an RFID tag	P_{TH}
The wavelength of the carrier	λ	The angle made by the tag with the reader plane,	$\boldsymbol{\theta}$
The distance from reader to tag	d	Reader, tag impedance mismatch power losses	e_{tag}, e_{rd}
Non-directional power density	S	Polarization mismatch power losses	e_{pol}
Directional power density	S_D	The differential reflection coefficient of the tag modulator.	$\Delta\rho$

2.1. Argumentation/Derivation

First assume that electromagnetic waves propagate under ideal conditions, i.e. without dispersion. If high-frequency energy is emitted by an isotropic radiator, than the energy propagate uniformly in all directions. Areas with the same power density therefore form spheres ($A = 4\pi R^2$) around the radiator. The same amount of energy spreads out on an incremented spherical surface at an incremented spherical radius [5]. That means: the power density on the surface of a sphere is inversely proportional to the square of the radius of the sphere. So we get the equation to calculate non-directional power density.

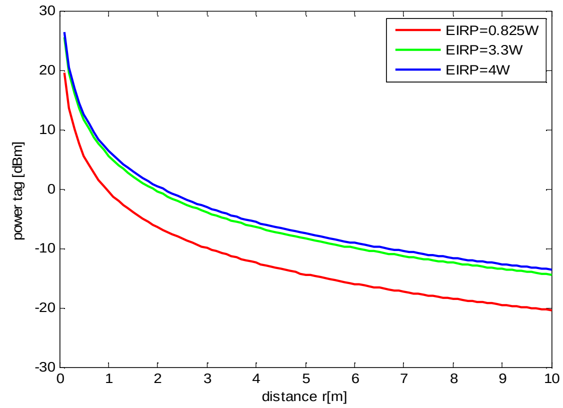

Fig. 2 Power received by tag before rectifier

$$S = \frac{P_{TR}}{4\pi r^2}\left[\frac{W}{m^2}\right] \qquad (3)$$

Since a spherical segment emits equal radiation in all direction (at constant transmit power), if the power radiated is redistributed to provide more radiation in one direction, then this results an increase of the power density in direction of the radiation. This effect is called antenna gain. This gain is obtained by directional radiation of the power. So, from the definition, the directional power density is:

$$S_D = S.G_R \qquad (4)$$

The target detection isn't only dependent on the power density at the target position, but also on how much power is reflected in the direction of the radar. In order to determine the useful reflected power, it is necessary to know the radar cross section σ. This quantity depends on several factors. But it is true to say that a bigger area reflects more power than a smaller area [15].With this in mind we can say: The received power at the radar depends on the power density S, the antenna gain of reader G_R, and the variable radar cross section σ:

$$P_{REC,READER} = S.G_R.\sigma\ [W] \qquad (5)$$

where

$$\sigma = \Delta_{RCS} = A_{eff}..(\Delta_\rho)^2 = \frac{\lambda^2 G^2 (\Delta\rho)^2}{4\pi} \qquad (6)$$

Because the reflected signal encounters the same conditions as the transmitted power, the power density yielded at the receiver of the reader is given by:

$$S_{REC} = \frac{P_{TR}G_R}{(4\pi)^2 d^4}.\sigma \qquad (7)$$

TABLE 2

POWER RECEIVED BY TAG AT DIFFERENT EIRP AND DISTANCES

F[MHz]	$\lambda[m]$	EIRP[dBm]	G [dBm]	d(m)	$P_{REC,TAG}$[dBm]
915	0.33	29	2	1	-0.4082
915	0.33	29	2	2	-6.4288
915	0.33	29	2	4	-12.4494
915	0.33	29	2	8	-18.4700
915	0.33	35	2	1	5.6124
915	0.33	35	2	2	-0.4082
915	0.33	35	2	4	-6.4288
915	0.33	35	2	8	-12.4494
915	0.33	36	2	1	6.4479
915	0.33	36	2	2	0.4273
915	0.33	36	2	4	-5.5933
915	0.33	36	2	8	-11.6139

The backscatter communication radio link budget, a modification of the monostatic radar equation, describes the amount of modulated power that is scattered from the RF tag to the reader :

$$P_{REC,READER} = S_{REC}.A_{eff} = \frac{P_{TR}G_R\sigma}{(4\pi)^2 d^4}.\frac{\lambda^2 G_R}{4\pi} = \frac{P_{TR}G_R{}^2\lambda^2\sigma}{(4\pi)^3 d^4} \qquad (8)$$

A_{eff} is the effective antenna aperture arises from the fact that an antenna suffer from losses, therefore, the received power at the antenna is not equal to the input power.

Fig. 3. shows plot of the backscatter link described by equation (8) for an RF tag. It is clear that the radio link which limits the range of such RFID system in free space is defined by the limitation imposed by the tag (20 ft), not by the reader (120 ft). The small amount of modulated power scattered from the RF tag is below the reader´s sensitivity threshold and therefore is undetected.

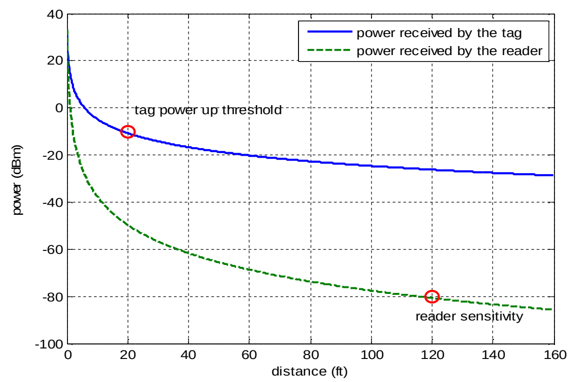

Fig. 3 Received power vs. distance for tag and reader in RFID system has EIRP=4W, F=915MHz and sensitivity=-80dBm, RFID chip sensitivity=-10 dBm, and chip impedance does not significantly change with absorbed power.

For successful operation, it is required that the ratio of the power received and transmitted from the reader not be too small. Fig. 4, shows an example of the ratios of the received signals for various situations at different frequencies.

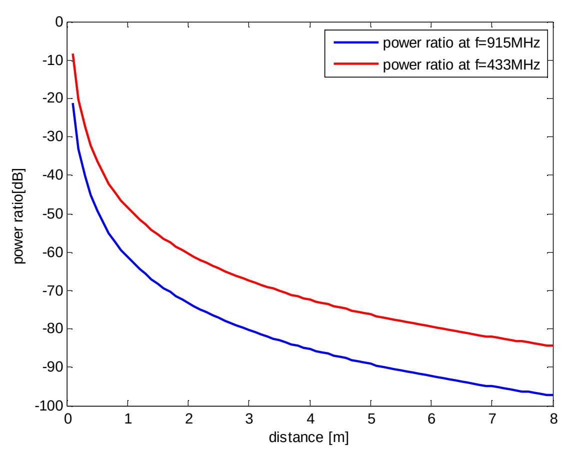

Fig. 4 Example of ratios of the power received when power transmitted of reader =33.01 dBm and $\Delta\boldsymbol{\rho}$=0.5

IV. READ/WRITE RANGE

The read/write range is the communication distance between the reader (interrogator) and tag. Specifically, the read range is the maximum distance to read data out from the tag, and the write range is the maximum distance to write data from the interrogator to the tag [2]. The read/write range is, among other effects, mainly related to electromagnetic coupling of the reader and tag antennas; the RF output power level of reader; carrier frequency bands; the power consumption of the device; antenna orientation; the distance between the interrogator and the tag; operating environment conditions (metallic, electric noise, multiple tags, multiple readers, and so on); etc[14]. The read range of a UHF-based RFID (propagation) system can be calculated by the Friis free-space equation as follows:

$$d = \frac{\lambda cos\theta}{4\pi}\sqrt{\frac{P_{TR}G_R G(1-(\Delta\rho)^2)}{P_{TH}}} \quad for \quad 0 \leq (\Delta\rho)^2 \leq 1 \qquad (9)$$

The far-field formula is subject to the assumption that the polarization of the reader and tag antennas which should be perfectly matched. However, in fact, the polarization mismatch is essential and required in most RFID applications [15]. The point is that in the majority of applications the tag is allowed to appear in an almost arbitrary position in the field of the reader antenna while the polarization of the tag antenna is usually linear because of the required small size of the tag. In such a situation, the only way to fulfill a system requirement is to use a circularly polarized reader antenna. Thus, a sacrifice of 3-dB power loss due to a polarization mismatch between a circularly polarized reader antenna and a linearly polarized tag antenna overcomes the problem of tag orientation [16]. In the case of linearly polarized reader and tag antennas, the substantial polarization misalignment may cause a severe power loss, which in its turn can potentially lead to a fault on the part of the RFID system [5]. In the case of a circular-to-linear polarization mismatch the read range *r* will be $\sqrt{2}$ times shorter than the one calculated by (9) [14]. As from the fig. 5 can see, systems operating in the 915-MHz band may achieve read ranges of 20 feet (6m) or more under current FCC regulations.

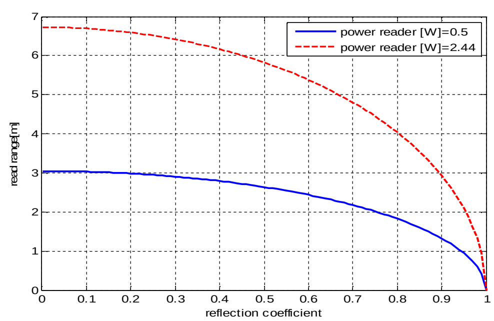

Fig. 5 Read range for different UHF reader powers and reflection coefficients at angle=0°

V. CONCLUSIONS

The analyses presented in this paper have demonstrated the clear relationship between the forward and reverse link in free space channel. Range of passive UHF RFID systems is limited by such factors as tag characteristics, propagation environment, and RFID reader parameters. Typically, reader sensitivity is high, and the tag limitation prevails. Tag range can be maximized by designing a high-gain antenna which is well matched to the chip impedance.

REFERENCES

[1] J. Landt, "The history of RFID", IEEE Potentials, vol. 24, no. 4, pp. 8-11, Oct.-Nov. 2005.

[2] W. C. Brown, "The history of power transmission by radio waves", IEEE Transactions on Microwave Theory and Techniques, vol. 32, no. 9, pp. 1230-1242, Sep. 1984.

[3] H. Cho, et al, H, "Design of an embedded-feed type microstrip patch antenna for UHF radio frequency identification tag on metallic objects," *IET Microw. Antennas Propag.*, Vol. 4, pp. 1232-1239, 2012.

[4] B. Khoo, " RFID as an enabler of the internet of things: issues of security and privacy", Proc. 2011 International Conference and 4th International Conference on Cyber, Physical and Social Computing, pp. 709-712, Oct. 2011.

[5] W. L. Stutzman and G. A. Thiele, Antenna Theory and Design, 2nd ed, Hoboken, NJ, John Wiley and Sons, 1998.

[6] K. Finkenzeller, Radio-Frequency Identification Fundamentals and Applications, 3rd ed, New York, John Wiley & sons Ltd, New York, 2004.

[7] J. Landt. "The history of RFID" IEEE Potentials, vol. 24, no. 4, pp. 8–11, Oct.-Nov. 2005.

[8] P. R. Agarwal1, P. R. Agarwal," RFID (Radio Frequency Identification) growth in daily life", International Journal of Scientific Engineering and Technology, vol. 1, no. 2, pp. 71-78, April 2012.

[9] T. Tang , G. H. Du. , " A slim wideband and conformal UHF RFID tag antenna based on u-shaped slots for metallic objects, Progress In Electromagnetics Research C, Vol. 38, pp. 141-151, 2013

[10] A. Rida et al. , RFID-Enabled Sensor Design and Applications, Boston-London, artechhouse, 2010

[11] H. Lehpamer, RFID Design Principles, 2nd ed., Boston, London, artechhouse, 2008.

[12] H. R. Anderson, Fixed Broadband Wireless: System Design, England, John Wiley & Sons Ltd, 2003.

[13] K. Penttila, M. Keskilammi, L. Sydanheimo, and M. Kivikoski, "Radar cross-section analysis for passive RFID systems," Inst. Elect. Eng. Proc., Micorw. Antennas Propag. , vol. 153, no. 1, pp. 103–109, Feb. 2006.

[14] G. Yanying, A. Lo, L. Niemegeers, "A survey of indoor positioning systems for wireless personal networks", IEEE Communications Surveys & Tutorials, vol. 11, no. 1, pp. 13 – 32, 2009.

[15] C. C. Yen, et al. ,"Radar cross-section analysis of backscattering RFID tags," IEEE Antennas Wireless Propag. Lett. , vol. 6, pp. 279–281, Jun. 2007.

[16] P. V. Nikitin and K. V. S. Rao, "Helical antenna for handheld UHF RFID reader," Proc. IEEE Int. Conf. on RFID, 166–173, May 2010.