UHF RFID TAG CHARACTERIZATION: OVERVIEW AND STATE-OF-THE-ART

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ABSTRACT

In this paper, we present an overview of UHF RFID tag performance characterization. We review the link budget of RFID system, explain different tag performance characteristics, and describe various testing methods. We also review state-of-the art test systems present on the market today.

Keywords: Measurement, RFID

1. Introduction

Radio frequency identification (RFID) based on modulated backscatter is a wireless technology with a long history [1]. Various RFID systems use different frequency bands: low frequency (LF, 125-134 kHz), high frequency (HF, 13.56 MHz) and ultra-high frequency (UHF, 860-960 MHz). They are different from traditional wireless systems where active transceivers communicate with each other. RFID transceiver (reader) transmits and receives simultaneously. The tag responds to the reader by varying its input impedance and thus modulating the backscattered signal. The tag itself can draw power from the RF energy of the reader signal (passive tags) or from the battery (battery assisted tags). In RFID, both forward and reverse links are important. Often the overall system performance is limited by the tags ("the weakest link"). Thus an accurate characterization of tag performance is crucial for both tag and system design.

2. Link Budget

Fig. 1 shows the graphical power link budget diagram of a monostatic RFID system, where the tag is located at a distance *d* away from the reader antenna. The horizontal axis is the distance, the vertical axis is the power. The power incident on the tag is

$$P_{inc} = EIRP\ G_{path} \quad , \tag{1}$$

where equivalent isotropic radiated power is $EIRP = P_t \tau_t G_t$, P_t is the reader output power, τ_t and G_t are the impedance matching coefficient and the gain of the reader antenna, G_{path} is the propagation path gain. The power absorbed by the tag IC is:

$$P_{abs} = P_{inc}\, pG\tau \quad , \tag{2}$$

where p is the polarization efficiency (also called the polarization loss factor), τ and G are the tag impedance matching coefficient and the gain of the tag antenna [2]. The backscattered power is then:

$$P_{bs} = P_{inc} K \, , \tag{3}$$

where K is the tag backscatter gain (a negative number). At the reader, the received tag signal power is:

$$P_r = P_{bs} G_{path}\ pG_t \tau_t \, . \tag{4}$$

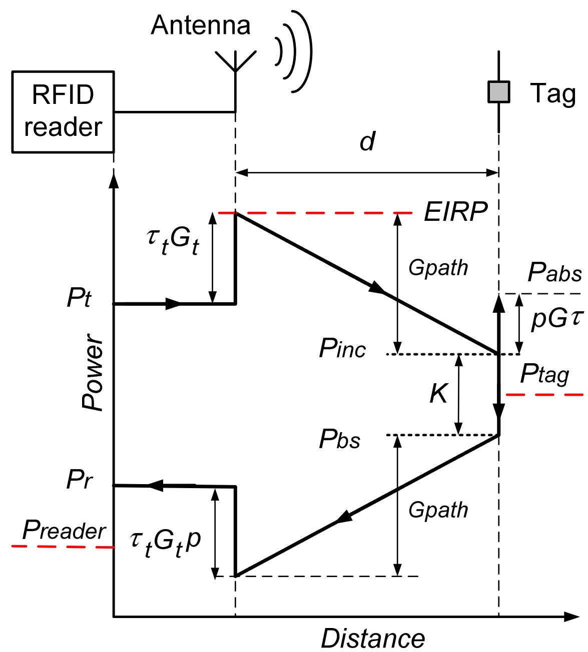

Figure 1 – RFID system link budget diagram.

In RFID systems, the forward link is limited by the tag sensitivity P_{tag} while the return link is limited by the reader sensitivity P_{reader}. When the incident power P_{inc} is larger than the tag sensitivity (or, equivalently, when the absorbed power P_{abs} is larger than the tag chip sensitivity P_{chip}), the tag is powered and responding. The reader can decode the tag response when the tag signal power P_r received at the reader is larger than the reader sensitivity. The reader sensitivity is the minimum power of the received tag signal required for successful decoding and is primarily defined by the level of self-jammer (the signal from the reader transmitter that couples into the reader receiver) which itself depends on transmitted power and receiver isolation. In general, the stronger is the self-jammer, the worse is the reader sensitivity.

Note that the diagram in Figure 1 is valid for monostatic system, far field scenarios (when readers/tags are far from each other) and free space-like environment (where the loss in the propagation channel is log-linear). It must be used with caution for bistatic systems, scenarios with near field interaction, and multipath channels.

3. Tag Performance Characteristics

Tag antennas and tag ICs can be characterized separately [3-5, 6-9], in a conducted or a wireless setup. Such measurements are important, but what really matters from the overall RFID system perspective is the radiated performance of the whole tag.

As mentioned before, in RFID systems, both forward and reverse links are important. The tag characteristic important for a forward link is the tag sensitivity - the minimum signal strength (field or power) at the tag location needed to read the tag. The tag power sensitivity is related to the chip (IC) sensitivity P_{chip} as:

$$P_{chip} = P_{tag}\, p\, G\, \tau\ . \qquad (5)$$

Write sensitivity usually differs from read sensitivity by a few dB's. Tag sensitivity is a function of frequency and can be calculated from the minimum power needed to activate the tag. Another characteristic often used is tag range, the maximum distance at which tag can be read (or written to) in free space [2]:

$$r_{tag} = \frac{\lambda}{4\pi}\sqrt{\frac{EIRP}{P_{tag}}}\ . \qquad (6)$$

Tag range is really a system characteristic because it assumes a free space environment and a certain reader transmitted *EIRP*. Figure 2 shows how tag read range depends on chip sensitivity and how both improved over the last dozen years for passive UHF RFID tags.

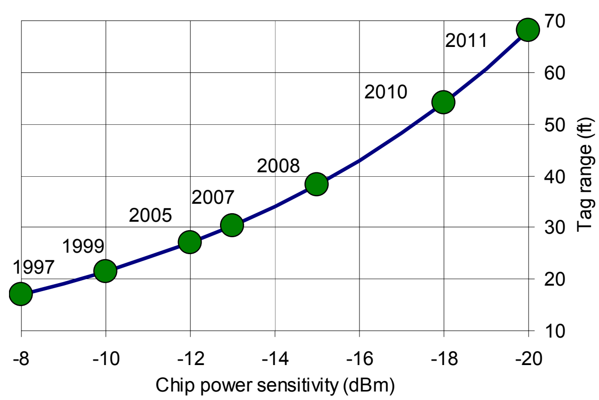

Figure 2 – Tag read range vs. chip sensitivity (4 W EIRP, free space, 915 MHz, 2 dBi matched tag).

The tag characteristic important for a reverse link is the tag backscatter gain:

$$K = pG^2\,\frac{|\rho_1 - \rho_2|^2}{4}\ , \qquad (7)$$

where ρ_1 and ρ_2 are the complex reflection coefficients between tag antenna impedance and chip impedance in both modulating states [10]. Tag backscatter gain is a function of frequency and incident power. An alternative equivalent tag characteristic is differential RCS [10-11]. Tag backscatter gain and differential RCS can both be calculated from the transmitted power and the signal strength of the received tag signal. A simple RF model which illustrates concurrent power collection and backscatter by the tag is given in Figure 3. An ideal circulator and a coupler show that one part of the incident RF power is absorbed while another part is converted to the modulated power and backscattered.

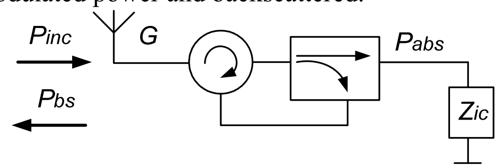

Figure 3 – Simple RF model of RFID tag.

One useful dependence is what reader sensitivity is needed to read an arbitrary tag at the maximum possible distance. Assuming polarization match between the tag and the reader antennas, the maximum path gain that allows the given tag to power up can be easily found from (1). Substituting that into (3) and (4), one can see that the needed reader sensitivity must be better or equal to:

$$P_{reader} = \frac{P_{tag}^2\, K}{P_t}\ . \qquad (8)$$

Note that the dependence given by (8) is valid for any propagation environment. It is illustrated in Figure 4 for four readers with four different output powers: 30 dBm, 20 dBm, 10 dBm, and 0 dBm (tag backscatter gain of -10 dB is assumed).

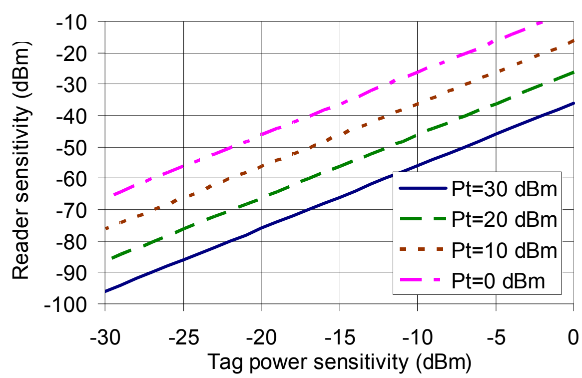

Figure 4 – Reader sensitivity needed to read tags of different sensitivity at their maximum possible range. The tag backscatter gain is assumed to be -10 dB.

4. Testing Methods and Environments

There are two main methods of measuring the tag performance. The first method is based on using fixed transmitter power and variable distance to the tag (*Pt* is constant, *d* is variable). This method does not require special equipment and is often used in practice to realistically measure tag range in various propagation environments. The second method is based on using variable power and fixed distance to the tag (*Pt* is variable, *d* is constant). The transmitted power is varied until the tag starts (or stops) responding. This method is often used in a controlled environment to obtain scientifically repeatable benchmark measurements.

Examples of controlled testing environments include anechoic chamber, transverse electromagnetic (TEM) cell, and reverberation chamber. Anechoic chamber such as the one shown in Figure 5 allows one to perform measurements of tags placed on different objects [12]. If either the reader antenna or the tag stand is motorized, the tag performance can be accurately measured for various orientations [13]. If anechoic chamber is not available, the reader antenna and the tag can be positioned close to each other, approximately 0.5-1 m away, to be in the far field zone and as far as possible away from the major reflectors to obtain repeatable results [14]. TEM cell, such as the one shown in Figure 6, is more broadband environment than an anechoic chamber and can be used, for example, for measurements of harmonics of the tag backscatter [15].

Of course, many practical RFID scenarios have very heavy multipath environments [16-22]. Reverberation chamber is an extreme case of a controlled heavy multipath environment which can also be used for tag testing [23].

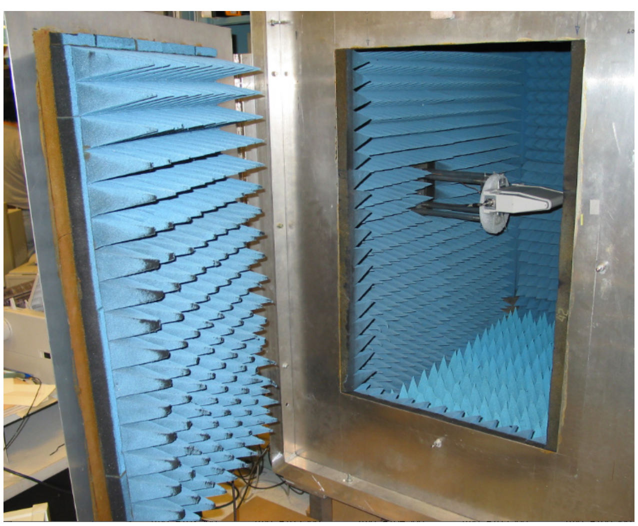

Figure 5 – Anechoic chamber used for tag measurements at Intermec.

Figure 6 – TEM cell TC-5060A.

5. Test Systems

As mentioned before, accurate wideband (preferably, 800-1000 MHz or wider) characterization of tag response is crucial for tag and system design [24]. The prevailing UHF RFID standard is ISO 18000-6C ("Gen2") [25]. In Gen2, a typical exchange of commands between the reader and a single tag during testing is illustrated in Figure 7. The reader queries the tag and receives its response containing the random number (RN16). In order to read tag EPC data or write data to the tag, the reader must process the tag RN16 response and acknowledge it within a restricted time window. This second step requires a real time processing capability from the tag test system.

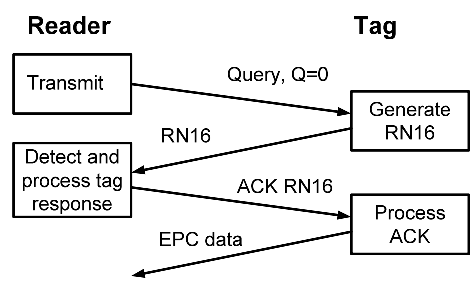

Figure 7 – Tag-reader command sequence.

Standard Gen2 readers have variable power but can only operate in fixed frequency bands (such as FCC, 902-928 MHz). There exists a variety of wideband test systems used by universities and companies. Some of those systems are available as commercial products. All test systems can be classified into four categories below.

1) Simple systems only detect the tag response presence but do not decode and process it. Such systems are often used in university labs and are typically based on a standard RF vector signal generator to produce a modulated command and RF spectrum analyzer to detect the tag response [11, 26-27].

2) Custom systems are based on some existing RFID reader hardware designed for certain tag protocol [28]. An example of such system is the system shown in Figure 8 (left) which was built for testing ISO 18000-6B tags.

Figure 8 – Intermec RFID test systems: left - custom system (1997), right - NI PXI system (2007).

3) Software defined radio (SDR) based RFID test systems are flexible and reconfigurable. They are typically based on National Instruments (NI) PCI eXtensions for Instrumentation (PXI) RF platform [24, 29-31] controlled by LabVIEW, such as the ones shown in Figures 8 (right), 9, and 10. Some of these systems are available as commercial products [32-33]. Such systems are extremely versatile and can be easily customized for specific RFID tag testing needs. They usually include an FPGA module to support a protocol command exchange illustrated in Figure 7. Other examples of SDR systems are given in [34-35] (those use Ettus USRP radio platform [36]).

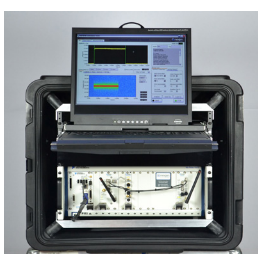

Figure 9 – Nexjen NI PXI RFID test system (image from [32]).

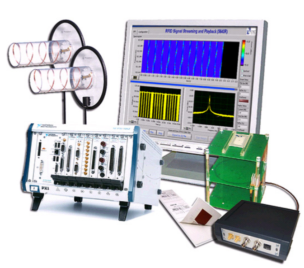

Figure 10 – CISC MeETS NI PXI RFID test system (image from [33]).

4) Portable commercial test systems can be easily transported and used in the field such as the ones shown in Figures 11, 12, and 13 [37-39]. These systems are wideband: TC-2600A [39] is 860-960 MHZ, Xplorer [38] is 800-1000 MHz, and Tagformance [37] is 700-1200 MHz. They can also be classified as SDR systems. A good overview of general SDR systems used for wireless testing and prototyping can be found in [40].

Figure 11 – Voyantic Tagformance Lite RFID test system (image from [37]).

Figure 12 – CISC RFID Xplorer test system (image from [38]).

Figure 13 – TESCOM TC-2600A RFID test system (image from [39]).

Many of the systems in the last two categories are more than just tag testers. They include such capabilities as phase measurement (important for tag localization applications [20]) or RFID tag emulation for reader conformance testing.

All systems listed above require some calibration, usually using a reference tag (with known characteristics). In addition to that, the user must carefully characterize the system components (cables, connectors, circulators, couplers, antennas, etc.) and take them into account when calculating tag characteristics from the quantities measured by the system (such as transmitted power or tag signal strength). In that regard the commercial systems are more user friendly. They are designed with all types of users in mind, including non-scientific ones, and often come with calibrated components whose values are already factored into the system software calculations. Some of these systems such as Voyantic [37] and CISC MeETS [33] are already widely used by the universities [41-42] and in the industry [31, 43].

6. Measurement Example

One typical example of measurements done with RFID test system is given below. It is the read range measurement performed by the system described in [24] and shown in Figure 8 (right). The measured tag was the Avery Dennison AD-223 [44] shown in Figure 14. This tag is based on Impinj Monza 3 IC and is often used in supply chain. It was tested in anechoic chamber (shown in Figure 5) for three cases: as is, on cardboard, and on plastic. The results are shown in Figure 15. Once can see that the wideband testing capability is important in this situation to understand how the tag resonances shift on different materials and how the tag read range is affected.

Figure 14 – AD-223 tag.

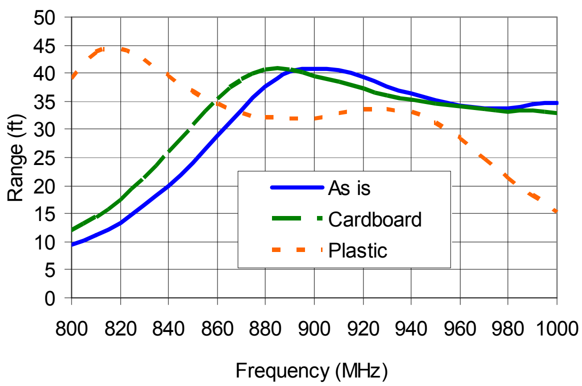

Figure 15 - Read range of AD-223 tag on different materials (4 W EIRP, free space).

7. Summary

In this paper, we presented an overview of UHF RFID tag performance characterization. We reviewed the link budget of RFID system, explained different tag performance characteristics, and reviewed test methods and systems. UHF RFID is still a developing technology looking for its killer application, but with plethora of tags present today, RFID tag testing systems already seem to have found their market niche and are widely used both by companies and universities.

8. References

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