Antennas and Propagation in UHF RFID Systems

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Abstract — **In this paper, we discuss antennas and propagation aspects in current passive UHF RFID systems. We consider a "reader-tag-reader" link and concentrate on each part of it: reader antennas, propagation channel, and tags. We include channel modeling equations and support our discussion with experimental measurements of tag performance in various conditions. We also provide a comprehensive literature review.**

I. INTRODUCTION

RADIO frequency identification (RFID) is an automatic wireless data collection technology with long history roots [1, 2]. In a passive RFID system, the reader transmits a modulated RF signal to the tag consisting of an antenna and an IC chip powered only by RF energy. The chip responds to the reader by varying its input impedance and thus modulating the backscattered signal. First functional passive RFID systems with a range of several meters appeared in early 1970's [3]. Since then, RFID has significantly advanced and experienced a tremendous growth [4, 5]. Multiple articles and several books dedicated to RF and other aspects of passive UHF RFID systems have been published in the recent years [6-9].

Performance of any wireless system depends on several antenna characteristics and propagation channel properties which include [10-12]:

- Antennas:
  - Operating frequency band;
  - Gain characteristics (maximum gain, radiation pattern, beamwidth, etc.);
  - Matching (VSWR or return loss);
  - Polarization (axial ratio);
  - Sensitivity to nearby objects with different properties.
- Propagation channel:
  - Path loss;
  - Spatial and temporal fading statistics (Ricean/ Rayleigh parameters, delay spread, coherence bandwidth, etc.).

Depending on wireless communication system, some of these characteristics may be more important than others (e.g. delay spread is an important bandwidth limiting factor in high data rate wireless communication systems). All antenna characteristics and channel properties described above are also important for RFID systems [13, 14]. However, passive UHF RFID systems based on modulated backscatter differ from traditional wireless systems which involve active transceivers on either side of the link (802.11, Bluetooth, etc.).
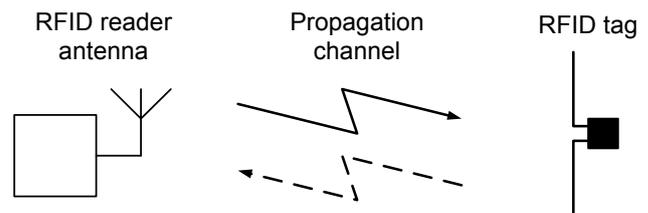

Figure 1. "Reader-tag-reader" link in passive UHF RFID system.

Tags (transponders) are powered only by RF energy, and RFID readers (transceivers) must transmit and receive simultaneously in order to be able to communicate with tags. This puts a different emphasis on some of the antennas and propagation aspects in "reader-tag-reader" link (shown in Figure 1) which we discuss in this paper, such as Tx/Rx isolation of RFID reader antenna system. We limit our discussion to far field region only. Near field UHF RFID is a separate subject which has been previously discussed in literature [15, 16] and which currently receives a lot of attention as a possible alternative to HF RFID for item level tagging and NFC applications [17].

II. RFID READER ANTENNAS

A. General Considerations

UHF RFID readers are transceivers which transmit and receive at the same time at the same frequency [18-20]. To maximize read range, readers typically transmit with maximum allowable EIRP using directional antennas with high gain. Good isolation between transmit and receive channels is very important for proper detection and decoding of weak tag signals. Sensitivity of current RFID readers is primarily defined by the leakage of transmitted signal into the receiver channel [9]. A number of different RFID readers, both portable and fixed, are commercially available. Detailed comparative performance evaluations of the most popular models can be found in [21].

Reader antenna is an important component of RFID system. General considerations for choosing RFID reader antennas, many varieties of which are available commercially, are well known [22-26]. An antenna choice is often limited by regional regulations for maximum allowable radiated power and antenna beamwidth in UHF RFID bands [27]. Depending on application, RFID systems can use advanced antennas such as switched beam antennas [28], polarization and space diversity antennas [29], smart antenna arrays [30], etc.

A very important design choice which defines the isolation between transmitting and receiving channels in RFID readers is RF front end antenna configuration [9, 18-20, 31, 32]. Two main choices are bistatic and monostatic configurations described below. A reader can also switch between these two configurations [19]. In both bistatic and monostatic cases, the presence of other objects near the antennas can generate reflections and significantly degrade antenna return loss and isolation between transmit and receive channels.

B. Bistatic Antenna Configuration

Bistatic configuration shown in Figure 2 uses separate transmit and receive antennas, separated in space and/or decoupled via polarization.
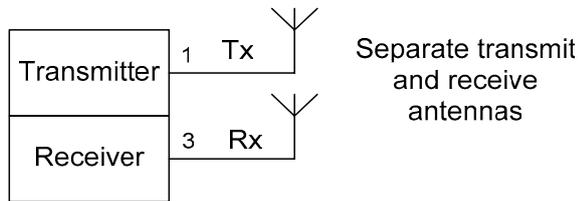

Figure 2. Bistatic antenna configuration.

Bistatic systems often use circularly polarized antennas, with opposite sense of polarization (RHCP and LHCP) for transmission and reception, which allows one to reduce antenna coupling and mitigate the effect of single multipath reflections. Bistatic systems find many uses in such applications as RFID portals and dock doors where more space is available for mounting several antennas [33].

C. Monostatic Antenna Configuration

Monostatic configuration shown in Figure 3 uses some type of RF isolator [34-35] and a single antenna to transmit and receive as shown in Figure 3. Two most common choices of isolators in RFID readers are circulators [36] and directional couplers [37-40]. In general, monostatic configurations have poorer isolation between transmit and receive channels compared to bistatic configurations.
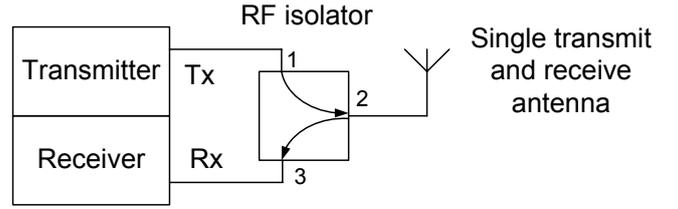

Figure 3. Monostatic antenna configuration.

In handheld RFID readers, monostatic configuration is often the only choice due to antenna size constraints. There, realizing a compact high gain wideband antenna with desired beamwidth and polarization, often poses a technical challenge [22, 23].

When used in RFID reader front ends, directional couplers introduce additional receive path attenuation loss compared to circulators. This requires better radio sensitivity from the receiver. However, the SNR of the received tag signal is limited not by the thermal noise but by the transmitted signal leakage [9]. In monostatic configurations, Tx/Rx isolation is often defined by the return loss of the antenna itself. As a result, tag signal SNR is approximately the same both for directional couplers and circulators as illustrated in the example in Table 1, where some typical values are used.

Table 1: Tag signal SNR for front end antenna configurations shown in Figures 2 and 3 and for two RF isolators: directional coupler and circulator (P_r is the tag signal power at the receiver, P_t is transmitter output power).

	Bistatic	Monostatic	
		Coupler	Circulator
Antenna return loss [dB]	-20	-20	-20
Coupling between antennas [dB]	-30	n/a	n/a
Isolator S12 [dB]	n/a	-1	-1
Isolator S23 [dB]	n/a	-20	-1
Isolator S13 [dB]	n/a	-45	-25
Isolation between Tx/Rx ports [dB]	-30	-41	-22
Tag signal SNR	P_r/P_t +30 dB	P_r/P_t +21 dB	P_r/P_t +21 dB

RFID readers can also have transmit and receive outputs and inputs switched between multiple ports in order to accommodate applications such as portals or forklift readers where multiple antennas are required to guarantee reliable tag reading. Each monostatic reader port requires one antenna; each bistatic reader port requires two antennas [20].

D. Polarization

Polarization is another important consideration for RFID reader antennas. For maximizing tag range, antenna polarization of the tag must be matched to that of the reader antenna. In most general case, both reader and tag antennas are elliptically polarized with mutually tilted axis of the polarization. The mutual polarization efficiency can be expressed as [41]:

$$p = \frac{1 + e_1^2 e_2^2 + 2e_1 e_2 \cos(\vartheta_1 - \vartheta_2)}{(1 + e_1^2)(1 + e_2^2)} ,\qquad(1)$$

where $e_1 e^{j\vartheta_1}$ and $e_2 e^{j\vartheta_2}$ are the complex polarization ratios of the reader antenna and the tag antenna. The absolute value e of the antenna polarization ratio is related to the antenna axial ratio A as [42]:

$$A[dB] = 20\log\left|\frac{e+1}{e-1}\right| .\qquad(2)$$

For example, when the reader antenna is circularly polarized with the axial ratio 0 dB and the tag antenna is linearly polarized, the best achievable polarization efficiency is 0.5 which translates into 70% of maximum possible tag range (see equation 16).

Most RFID tags available on the market are linearly polarized. At the same time, many RFID reader systems use circular polarized antennas to ensure that tags can be read in any orientation. These antennas are often specified by their circular gain and axial ratio. Because tag range strongly depends on antenna gain, it is important to understand the relationship between the linear gain of an antenna and its circular gain. Linear gain is referenced to a linear isotropic source and measured in *dBil*, while circular gain is referenced to a circularly polarized isotropic source and measured in *dBic*. The two gains are related as [42-44]:

$$G[dBic] = G[dBil] + 3 + 20\log\left(\frac{1 + 10^{-A/20}}{2}\right).\qquad(3)$$

The common notion that the difference between the two gains is 3 dB is true only for perfect circular polarization, which is almost never the case in practice. Depending on axial ratio, circular gain of the antenna can be higher or lower than its linear gain [44].

III. PROPAGATION CHANNEL

A. Path Loss

Path loss between the two communicating antennas strongly depends on the propagation environment and has been extensively studied in wireless communications [9-12]. In the recent years, there appeared several articles with studies and analysis of propagation environment specifically in application to UHF RFID systems [45-54].

In a multipath environment with the line-of-sight and several single reflections, the path loss between the reader and the tag antennas can be written as [50]:

$$L_{path} = \left(\frac{\lambda}{4\pi d}\right)^2 \left|1 + \sum_{n=1}^{N} \Gamma_n \frac{d}{d_n} e^{-jk(d_n - d)}\right|^2 ,\qquad(4)$$

where d is the length of the direct ray path, Γ_n is the reflection coefficient of the n-th reflecting object (including ground), d_n is the length of the n-th reflected ray path, and N is the total number of reflections. Depending on the environment, the path loss can behave as d^{-n}, where path loss exponent n may vary between 1 and 6.

As an example, consider an RFID system where both the reader and the tag antennas are positioned at the height h above the ground as shown in Figure 4.
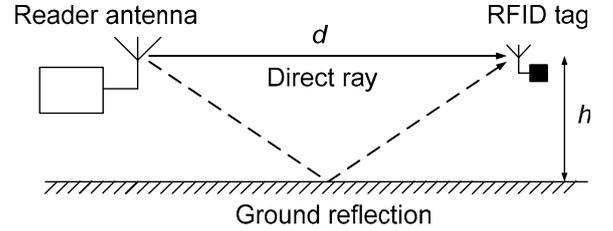

Figure 4. Path loss example: 2-ray ground reflection case.

This is a classical 2-ray ground reflection case [55]. The amplitude and phase of the ground reflection depend on wave polarization, angle of incidence, and ground properties. For simplicity, assume isotropic antenna patterns and ideal reflection from the ground (reflection coefficient is equal to -1). The path loss in this case is given by the following 2-ray ground reflection model:

$$L_{path} = \left(\frac{\lambda}{4\pi d}\right)^2 \left|1 - \frac{d}{d_1} e^{-jk(d_1 - d)}\right|^2 ,\qquad(5)$$

where d is the line-of-sight distance to the tag, and $d_1 = \sqrt{d^2 + (2h)^2}$ is the reflected ray path length. At long distances $(d >>= 4\pi h^2/\lambda)$, the path loss given by (5) becomes proportional to d^{-4}.

The signal strength at the tag location can be obtained from the path loss as:

$$P_{tag} = P_t G_t L_{path} ,\qquad(6)$$

where P_t is the output power of the RFID reader transmitter and G_t is the gain of the reader antenna ($P_t G_t$ is the transmitted EIRP). The signal strength at the tag location can be interpreted as the power absorbed by the RFID chip connected to a perfectly matched 0 dBi tag antenna.
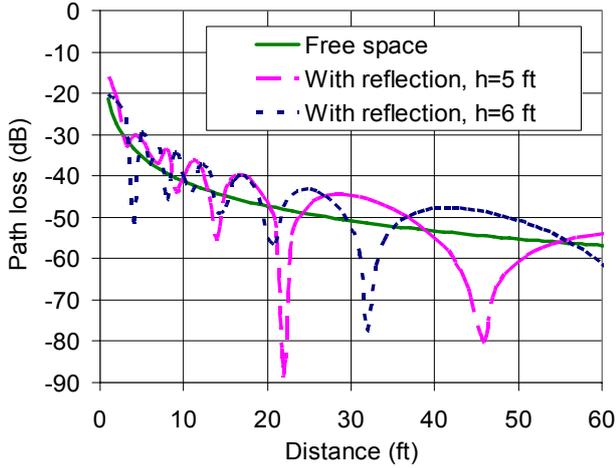
Figure 5. Path loss (dB) vs. distance (ft) in ground reflection example at 915 MHz for two different antenna heights.

The path loss given by (5) is plotted in Figure 5 at 915 MHz for two different antenna heights above the ground. One can see that the transmitted signal will experience significant variations with distance due to multipath.

Assume that the reader transmits 4 W EIRP (36 dBm). Assume also that a tag has an RFID chip with -12 dBm threshold power sensitivity and 2 dBi perfectly matched antenna. These numbers are typical for many current flexible Gen2 inlays which use dipole-like antennas and Impinj Monza 2 RFID IC [20], well matched together. Such tag would need incident signal strength of -14 dBm in order to power up. Thus, the maximum read distance for such tag would be limited by a path loss of -50 dB. From Figure 5, the path loss of -50 dB corresponds to maximum tag range of 27 ft in free space. The presence of ground reflection can extend this distance to 37 ft (if h=5 ft) or 48 ft (if h=6 ft) but will also create dead zones within that range which correspond to locations where the path loss is below -50 dB.

In reality, the situation may be far more complex due to multiple reflections from different objects, diffraction, shadowing, etc. Because of the relatively low data rate of UHF RFID systems (<640 kbps for Gen2 protocol [27]), the typical indoor RMS delay spread of less than 300 ns [56] is usually not an issue, and the communication link between the reader and the tag is primarily affected by the received signal power. Some low loss propagation environments can have path loss significantly lower than free space, and, as a result, much longer tag read distance. An example is waveguide-like environment where waves propagate only along dominant directions (pipes, ducts, tunnels, etc.) [57, 58].

Note that any real propagation environment, no matter how complex, is always symmetrical – the path losses of the forward and reverse channels between the two communicating antennas are equal. Any measured asymmetry is usually due to RF hardware calibration.

B. Forward and Reverse Channels

Forward channel is the "reader-tag" link. The path loss of the forward channel defines maximum tag range in the tag power limited case – when the reader sensitivity is high so that it can detect the tag as soon as it gets powered up and starts backscattering. Reverse (backscatter) channel is the "tag-reader" link. The path loss of the reverse channel defines the maximum tag range in RFID system in the reader sensitivity limited case – when the tag sensitivity is so high that it remains powered up even at distances where the reader can no longer detect it. Both channels have been extensively discussed in RFID literature [45-53, 59-61].

Passive UHF tag essentially receives incident RF power and converts it to modulated backscattered power. It can be viewed as an RF source emitting a modulated signal with the following differential EIRP:

$$\Delta EIRP = S\Delta\sigma = P_{tag}G^2K \ , \tag{7}$$

where G is the gain of the tag antenna, $\Delta\sigma$ is the tag differential RCS, K is the modulation loss (both are discussed in details in the next section), and S is the power density of an electromagnetic wave with the electric field E incident on the RFID tag, given in free space by:

$$S = \frac{E^2}{120\pi} = \frac{P_t G_t}{4\pi d^2} \ , \tag{8}$$

where d is the distance to the tag. The power of the tag signal received by the monostatic reader antenna in an arbitrary propagation environment can be written as:

$$P_r = G_t L_{path} \Delta EIRP \ . \tag{9}$$

In free space, equation (9) can be rewritten in the form of a classical radar equation [62]:

$$P_r = P_t G_t^2 \frac{\lambda^2 \Delta\sigma}{(4\pi)^3 d^4} = P_t G_t^2 \left(\frac{\lambda}{4\pi d}\right)^4 G^2K \ . \tag{10}$$

Equation (10) is useful for reader link budget calculations in RFID systems [9, 20].

IV. RFID TAGS

A. General Considerations

Particular RFID applications often define tag form factors and require specific tag performance (such as range, directionality, sensitivity to materials, etc.). This, as well as operating frequency band, often restricts tag antenna choice and puts limits on maximum attainable tag antenna gain. However the best possible impedance match between the antenna and the RFID chip is always important for the best tag performance. Since RFID chip impedance depends on both frequency and absorbed power, matching for maximum tag range is usually done at the chip threshold power level.

Many important aspects of RFID tag antenna design have been covered in existing literature [6-9, 63-66]. These aspects include optimization of tag antenna gain, polarization, directionality, impedance matching, etc. A large number of various RFID tags, both flexible and rigid, are commercially available from different companies [67-75]. Detailed comparative performance evaluations of various tags can be found in [76, 77]. Below, we concentrate on three main tag performance characteristics and methods of measuring them, specifically:

- Tag sensitivity;
- Tag range;
- Tag differential RCS.

B. Tag Sensitivity

Tag sensitivity is the minimum signal strength (field or power) at the tag location needed to power up (read) the tag. This fundamental tag performance characteristic is independent of the power transmitted by the reader or propagation environment. It is a function of the chip threshold power sensitivity, tag antenna gain, and match between tag antenna and high (power collecting) impedance state of the chip.

Tag field sensitivity E_{tag} (V/m) and power sensitivity P_{tag} (W) are directly related. The power collected by a perfectly matched antenna load (chip) can be expressed either via incident power and tag antenna gain or via incident power density and effective tag antenna area:

$$P_{tag}\, G = S\, A_e , \qquad (11)$$

where the effective area of an RFID tag antenna A_e is:

$$A_e = \frac{\lambda^2}{4\pi} G . \qquad (12)$$

Combining (8), (11), and (12), one can obtain that

$$E_{tag} = \frac{4\pi}{\lambda} \sqrt{30 P_{tag}} . \qquad (13)$$

The relationship given by (12) is plotted in Figure 6 for frequency 915 MHz.
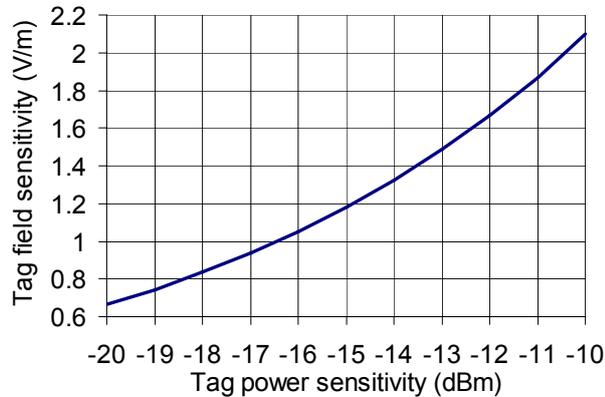

Figure 6. Tag field sensitivity (V/m) vs. tag power sensitivity (dBm), frequency is 915 MHz.

Tag power sensitivity can also be readily expressed as:

$$P_{tag} = G\, p\, \tau\, P_{th} , \qquad (14)$$

where p is the polarization efficiency, τ is the impedance matching coefficient between the tag antenna and the chip, and P_{th} is the chip power threshold sensitivity. Equation (14) shows how much minimum incident power at the tag location is needed to make sure that the sufficient amount of it gets absorbed in the RFID chip and activates it.

Write sensitivity differs from read sensitivity, typically by about 3 dB, because RFID IC needs more power for performing write operation.

C. Tag Range

Tag range is typically defined as the maximum distance at which tag can be read. It is an easily understandable, directly measurable, and thus commonly used tag performance characteristic. This characteristic depends not only on tag sensitivity but also on system parameters. It is a function of EIRP transmitted by the reader, propagation environment path loss, and tag sensitivity. Similar to sensitivity, write range (maximum distance at which the tag can be written to) is usually lower than read range (typically, 70% of it).

Assuming that the maximum read distance is limited only by the tag sensitivity, we can calculate the tag range in an arbitrary propagation environment by solving the following link budget equation which equates signal strength at the tag location to the tag power sensitivity:

$$P_t G_t\, L_{path}(d)\, = P_{tag} . \qquad (15)$$

In special cases, when an inverse function of distance-dependent path loss $L_{path}^{-1}(d)$ can be found in an analytical form, equation (15) can also be analytically solved for tag range. The most well known classical special case is again free space, where the path loss is proportional to d^{-2} [78, 79] and the tag range can be found to be:

$$r_{tag} = \frac{\lambda}{4\pi} \sqrt{\frac{P_t G_t\, G\, p\, \tau}{P_{th}}} . \qquad (16)$$

One can see that the tag range in free space is related to the tag field sensitivity and the tag power sensitivity as

$$r_{tag} = \frac{\sqrt{30 P_t G_t}}{E_{tag}} = \frac{\lambda}{4\pi} \sqrt{\frac{P_t G_t}{P_{tag}}} . \qquad (17)$$

The relationship between tag range and field sensitivity given by (17) is plotted in Figure 7. Tag range dependence on chip threshold power sensitivity, tag antenna gain, and impedance matching between chip and tag antenna are plotted in Figures 8, 9, and 10. Once again, we assume that the reader transmits 4 W EIRP in free space at 915 MHz and imply where needed that the tag antenna has a gain of 2 dBi, the tag IC has a power sensitivity of -12 dBm, and the impedance matching coefficient is 1. Such "reference tag" has a range of 27 ft and is marked as a circle on all plots in Figures 7-10.
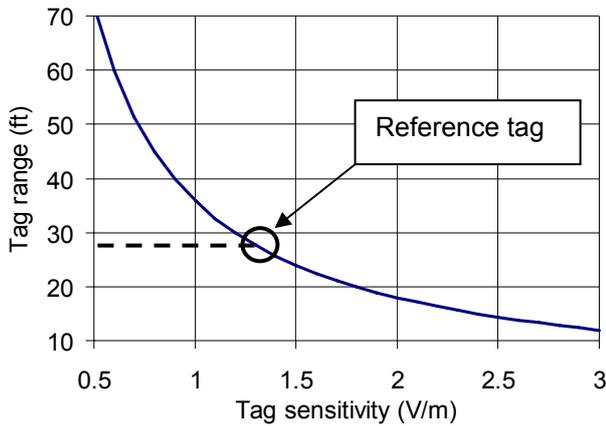
Figure 7. Tag range (ft) vs. tag field sensitivity (V/m). Other parameters: free space, 4 W EIRP.

Figure 8. Tag range (ft) vs. chip power sensitivity (dBm). Other parameters: free space, 4 W EIRP, 915 MHz, 2 dBi tag antenna, perfect impedance match.

Figure 9. Tag range (ft) vs. tag antenna gain (dBi). Other parameters: free space, 4 W EIRP, 915 MHz, -12 dBm chip sensitivity, perfect impedance match.
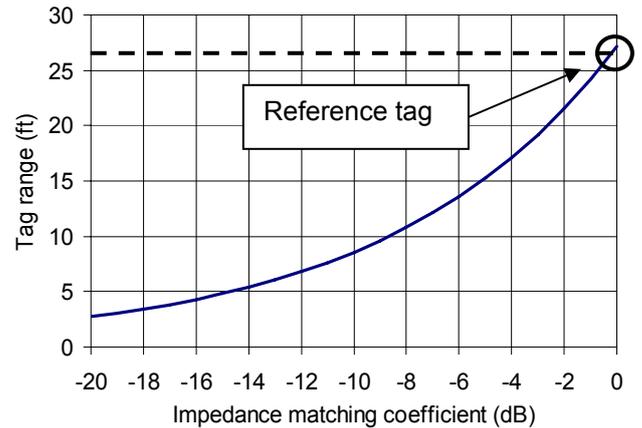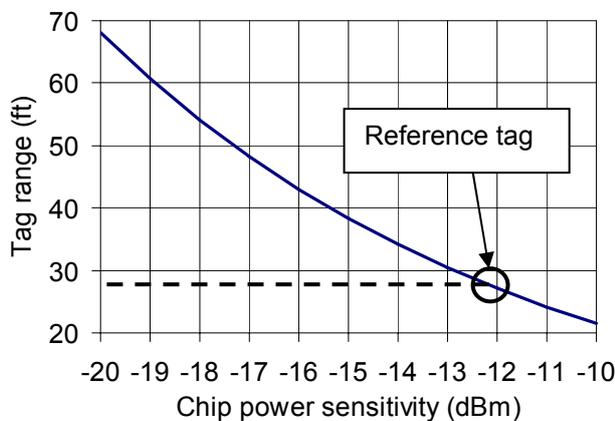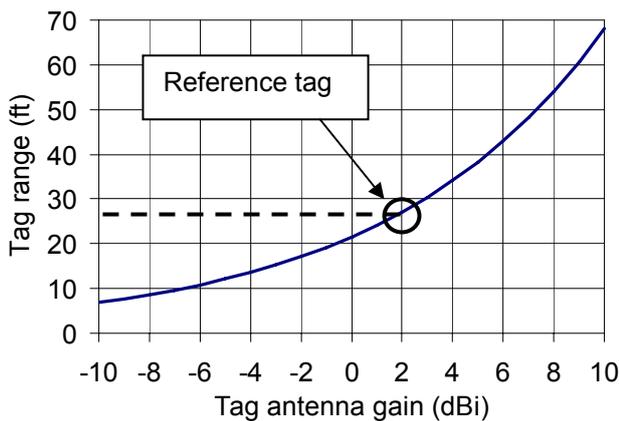

Figure 10. Tag range (ft) vs. impedance matching coefficient (dB). Other parameters: free space, 4 W EIRP, 915 MHz, -12 dBm chip sensitivity, 2 dBi tag antenna.

Currently, the maximum range of passive RFID systems is limited by the tag sensitivity. However, when the tag sensitivity is very high, such as in the case of battery assisted (semi-passive) tags, the range becomes limited by the reader sensitivity. Note that tag range in passive UHF RFID systems can also be severely affected by various types of interference, such as tag-on-tag, reader-on-tag, reader-on-reader, and interference from external EMI sources, etc. All these subjects deserve separate discussions and have been covered in literature [61, 80-88].

D. Differential RCS

Differential RCS $\Delta\sigma$ (also known as delta RCS) of an RFID tag is yet another tag performance characteristic. Like tag sensitivity, this characteristic depends only on tag itself and determines the power of the modulated signal backscattered to the reader. It is a function of the tag antenna gain and the matching between the tag antenna and the two modulating states (high and low) of the chip impedance.

Classical radar theory uses scalar RCS [62]. Scalar RCS of an RFID tag antenna connected to any particular load can be found directly from classical theory of loaded scattering antennas [89] and has been discussed in literature [90-91]. However, RCS is a complex quantity [92]. Citing [92], "scalar RCS is like identifying people by their weight". The phase of the signal received from the tag in each state is also important and depends on several factors such as phase of the field reflected from the tag, propagation environment, phase shifts of various RFID system components, etc. The differential RCS depends on relative magnitudes and phases of the backscattered field and is not a mere difference of two scalar RCS values. Two chip impedance states may result in the same scalar RCS values for the tag but produce non-zero modulated backscattered power.

Differential RCS of a tag can be defined as shown in [93]:

$$\Delta\sigma = A_e K\, G = \frac{\lambda^2}{4\pi} G^2\, K \;, \qquad (18)$$

where K is the modulation loss which depends both on chip and antenna parameters and can be written as:

$$K = \alpha\,|\rho_1 - \rho_2|^2 \;. \qquad (19)$$

The coefficient α depends on the specific modulation details and ρ_1 and ρ_2 are the reflection coefficients between tag antenna impedance Z_a and chip impedance $Z_{1,2}$ in modulating states 1 and 2:

$$\rho_{1,2} = \frac{Z_{1,2} - Z_a^*}{Z_{1,2} + Z_a} \;. \qquad (20)$$

In reality, since in most cases the tag antenna is well matched to the chip, with impedance approximating complex conjugate of the chip high impedance state, the modulation loss is primarily defined by the RFID chip characteristics. However, the tag antenna is also important since the product $G^2 K$ defines how much of the incident RF power the tag is able to convert to the modulated backscattered power.

The definition of delta RCS given in [93] uses coefficient $\alpha = 1$, which corresponds to the maximum observable magnitude of vector difference between the two complex RCS values of RFID tag in two states. This agrees with the classical antenna theory which implies that the maximum observable RCS of the minimum scattering antenna switching between open and matched loads is equal to the scalar RCS of the same antenna connected to the matched load (in such loaded antenna the scattered power and the power dissipated in the matched load are equal). However, this definition does not take into account modulation details needed to calculate time average signal power. It also uses one of the modulating states as a reference which introduces an additional DC offset into the signal (when the tag signal is processed by RFID reader, the DC offset is normally removed and does not contribute to the signal power).

Assume that the modulated tag signal has 50% duty cycle (Gen2 FM0 signaling scheme [27]) and the reference level of the received voltage is the mid-point between modulating states (DC offset is zero). Then one can easily calculate that the coefficient α in this case is 1/4. Table 2 gives modulation loss factor for different chip impedance state pair combinations. One can see that the maximum modulation efficiency is obtained when the impedance is switched between short and open states (180 degrees phase modulation). This choice of modulating states does not allow for any RF signal power to be collected by antenna load (RFID chip) but is a good choice for semi-passive tags. In tags, typical choice of modulating states is matched and short, which results in -6 dB modulation loss. Excellent

analysis of design considerations and tradeoffs for backscatter modulation schemes can be found in [8, 9]. Differential RCS and modulation loss K can be calculated from the received power of tag signal given by (10).

Table 2: Modulation loss K for different chip impedance state pairs (50% duty cycle and zero DC offset are assumed).

Z_1	Matched	Matched	Short
Z_2	Short	Open	Open
ρ_1	0	0	-1
ρ_2	-1	1	1
K	-6 dB	-6 dB	0 dB

V. MEASUREMENTS

A. Systems and Methods

Accurate measurements of tag performance are crucial for quality tag design implementation and verification [64, 76, 77, 94, 95]. RFID tag testing systems and methods have significantly advanced in the recent years. Both specialized wideband systems as well as band-specific reader-based systems are now being used for tag performance measurements. Many RFID testing labs and companies start using flexible reconfigurable wideband systems, such as based on National Instruments PXI RF hardware controlled by LabVIEW or other custom hardware [95-99].

Two main methods of measuring tag performance are described below. First method uses fixed transmitted power and variable distance to the tag. This method does not require special equipment and is often used in RFID practice. The reader transmits with constant power while the tag is being moved away until it cannot be read. This allows one to realistically measure tag range in various propagation environments. In reflection-free environment, the tag sensitivity can be calculated from the tag range using (17). Second method uses variable power and fixed distance to the tag. The transmitted power is varied to find the minimum value at which the tag becomes detectable. This allows one to perform scientifically repeatable benchmark measurements even in compact anechoic chamber. From our experience, the results of this test method correlate very well with real outdoor range measurements.

Tag power sensitivity and maximum tag range for any given EIRP can be calculated from the measured minimum power using the following equations:

$$P_{tag} = P_{min} G_t \left(\frac{\lambda}{4\pi d}\right)^2, \qquad (21)$$

$$r_{tag} = d\sqrt{\frac{EIRP}{P_{min} G_t}} \;. \qquad (22)$$

Tag sensitivity measurements can also be performed in other controlled environments, such as TEM cell.

To illustrate some of the points discussed in this paper, we conducted several experiments. Specifically, we performed three sets of measurements described further in this section:

- Tag sensitivity, range, delta RCS, and modulation loss;
- Multipath effect on signal strength at tag location;
- Interference effect on tag sensitivity.

We used experimental setup shown in Figure 11 where the tag was placed at fixed distance (d=3 ft) from the reader antenna. The measurement equipment was National Instruments LabVIEW-controlled PXI RF system [99] which functioned as an RFID reader with variable frequency and output power, operating in 800-1000 MHz frequency band. It allowed us to measure both the minimum power needed for tag to respond and the tag backscatter signal strength. We used a standard UHF RFID reader antenna made by Sinclair Technologies (model number SRL441U) [100] and shown in Figure 12. The antenna was linearly polarized, with approximately 6 dBi gain. The anechoic chamber size was 4 x 4 x 6 ft. The tag was standard commercially available EPC Gen2 inlay made by Avery Dennison (model number AD-431) [68] and shown in Figure 13. The tag was oriented to match the reader antenna polarization. Correction factors such as transmitting antenna gain variations with frequency, connector and cable losses, etc. were also measured and taken into account in our measurements. The AD-431 tag antenna was simulated using *Ansoft Designer* and the gain was found to be close to 2 dBi.
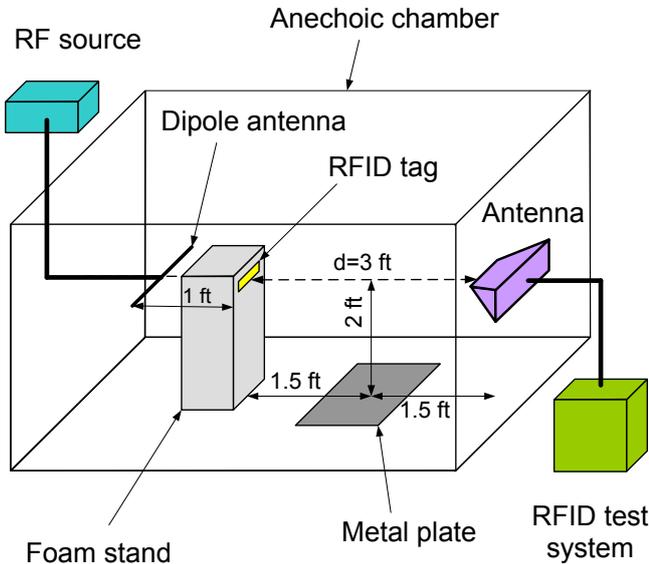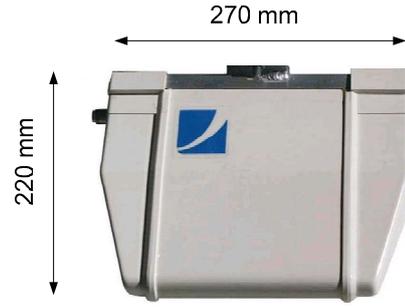

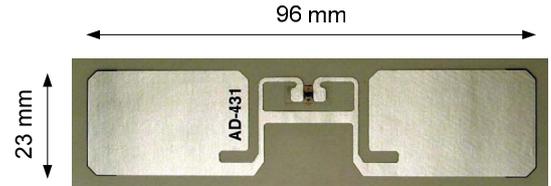Fig. 12. RFID reader antenna used in measurements (Sinclair SRL441U).

Figure 13. Tag used in measurements (Avery Dennison AD-431).

C. Tag Range, Sensitivity, and Differential RCS

In this experiment, we measured the minimum transmitter power P_{min} needed to turn on the tag and calculated tag power sensitivity and range from equations (21) and (22). The results are shown in Figure 14. One can see that the best tag sensitivity values correspond to the best tag range and vice versa.

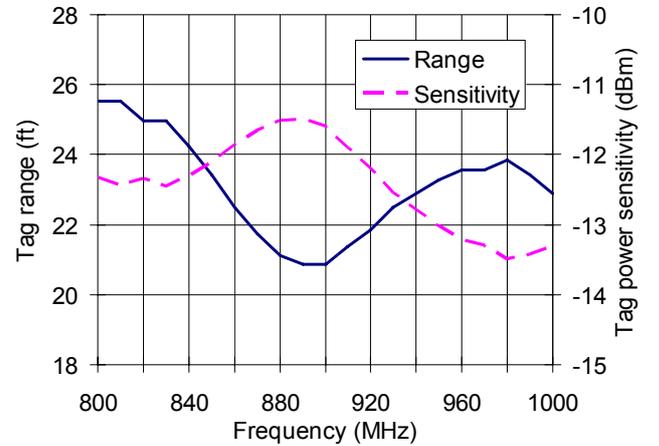Figure 11. Experimental setup.

Figure 14. Tag power sensitivity (dBm) and range (ft) vs. frequency. Other parameters: free space, 4 W EIRP.

We also measured the received tag signal strength at the RFID receiver and calculated corresponding tag differential RCS, modulation loss, and differential EIRP using (10) as functions of the transmitter power (which can also be recalculated into the equivalent free-space distance from 4 W EIRP source which would result in the same signal strength at the tag location).

Figure 15 shows the received tag signal power and the tag delta RCS as functions of the transmitter power. Figure 16 shows the tag modulation loss and the differential EIRP as functions of the distance from 4 W EIRP source. The minimum transmitter power needed to activate the tag at 870 MHz in our setup was 14 dBm. One can see that as the power incident on the tag increases, the tag increases its modulation loss, reducing its differential RCS. This regulates the backscattered signal level, causing differential EIRP to remain fairly constant (it varies only by 5 dB while the transmitter power varies by 16 dB). The maximum measured modulation loss (approximately -11 dB) was at the lowest power incident to the tag (equivalent to the maximum tag range).
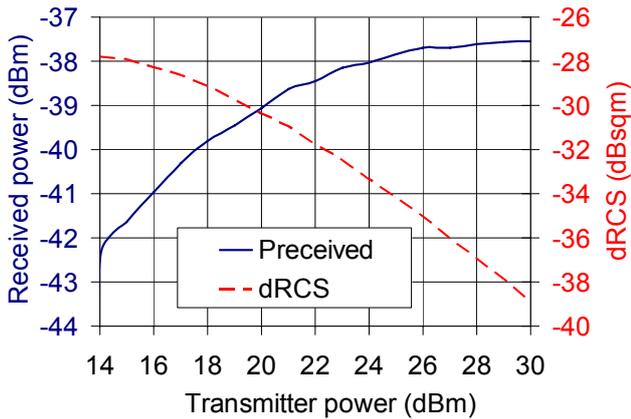

Figure 15. Tag signal power received by the reader (dBm) and tag differential RCS (dBsqm) as functions of the output power of the reader transmitter. Other parameters: free space, d=3 ft, frequency is 870 MHz, reader antenna gain is 6 dBi (transmitted power of 30 dBm corresponds to 36 dBm EIRP).
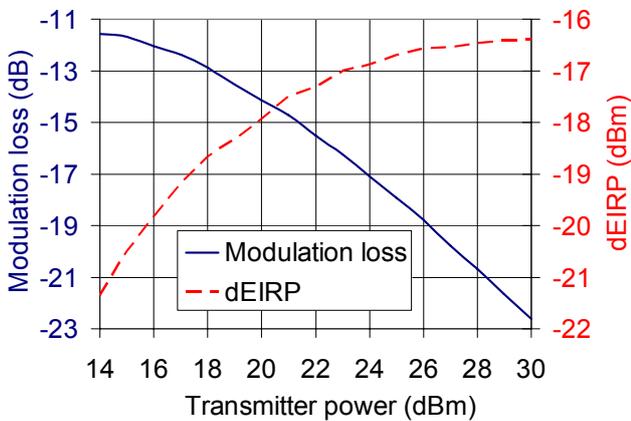

Figure 16. Tag modulation loss (dB) and differential EIRP (dBm) as functions of distance. Other parameters: free space, 4 W EIRP, frequency is 870 MHz.

D. Multipath Effect on Signal Strength at Tag Location

In this experiment, we measured the effect of multipath on the performance of RFID system. A metal plate (1 ft x 1 ft) was added to the bottom of the anechoic chamber at the mid-point between the tag and the reader antenna as shown in Figure 11. The tag sensitivity did not change but the presence of metal plate affected the signal strength at the tag location and thus the minimum power needed to power up the tag as shown in Figure 17. One can see that even in this simple scenario, the reflection caused by a single relatively small object can affect the link budget of RFID system by 1 dB or more (approximately 10% range difference). Note that tag range in this example cannot be directly calculated from the measurements because the environment is not free space, and multipath effects do not scale linearly with distance.
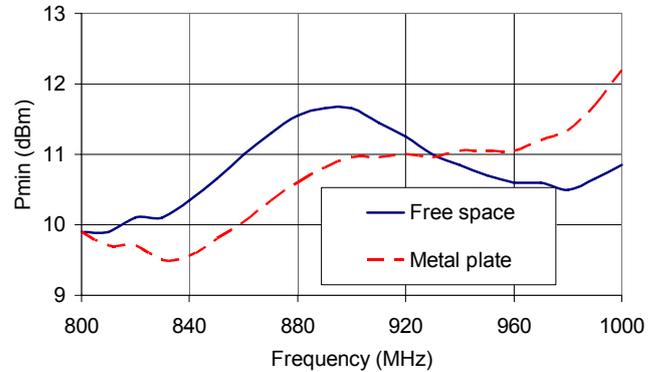

Figure 17. Minimum power (dBm) needed to read the tag in the absence and in the presence of metal plate and signal strength change (dB) at the tag vs. frequency (MHz).

E. Interference Effect on Tag Sensitivity

In this experiment, we measured tag sensitivity in free space environment in the presence of external EMI source, an RF signal generator transmitting a CW signal in UHF band. This auxiliary RF source had a constant power (8 dBm) and transmitted using a dipole antenna (~2 dBi gain) placed 1 ft behind the tag as shown in Figure 11. The tag power sensitivity was measured for different CW source frequencies: 850, 900, and 950 MHz. The results are shown in Figure 18. Note that in this particular experiment the presence of another antenna (dipole antenna of RF CW source) near the tag slightly affected the tag sensitivity, degrading it by approximately 0.5 dB (compare the baseline power sensitivity in Figure 18, when CW is off, with the power sensitivity in Figure 14).
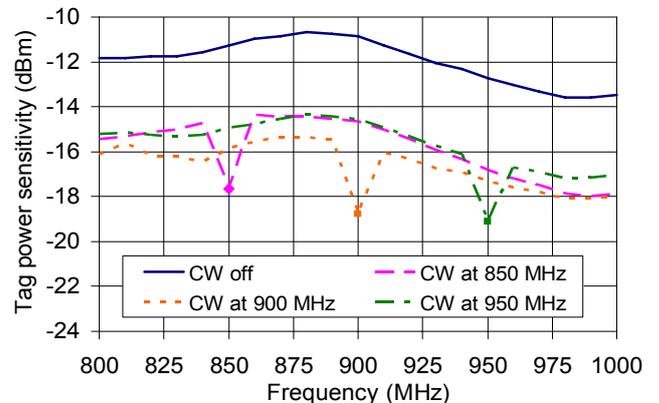

Figure 18. Tag power sensitivity (dBm) in the presence of external RF CW source transmitting in the tag vicinity.

One can see that the presence of external RF source can have drastic effect on RFID tag sensitivity. In this particular example, tag power sensitivity can be improved by up to 8 dB (at the frequency of 900 MHz in Figure 18) which translates into a tag range increase factor of 2.5.

The presence of external auxiliary RF source in UHF RFID band provides additional RF power to the passive tag, essentially turning it into "RF assisted" tag with much longer read range which can be used in various applications [101]. The particular sensitivity improvement depends on the power of auxiliary source (it must be in the certain range in order not to overpower the reader signal) and the specifics of RFID chip front end. It is most drastic at the frequency of RF CW source, but can also be observed at other frequencies. The observed sensitivity improvement in 800-1000 MHz band was at least 3 dB compared to baseline.

This example shows that EMI interference is an important factor which should be considered when RFID systems are deployed in the presence of other wireless communication systems, including other RFID systems. Depending on the situation, the interference caused by external RF sources can have positive or negative effect on tag range.

VI. CONCLUSIONS

RFID is a very dynamic discipline. In this paper, we presented a brief discussion of major antennas and propagation aspects which on our opinion are important in current passive UHF RFID systems. Some interesting recent technology developments related to antennas and propagation in UHF RFID systems include:

- Near-field UHF RFID [15-17];
- Semi-passive (BAP) RFID systems [102];
- Ultra-wide band RFID systems [103, 104];
- Tags for operating on metal [105-107];
- Tags with multiple antennas [108];
- Tags with low static scattering [109-111];
- Tags with sensor capabilities [112];
- New RFID ICs with better RF sensitivity [113];
- Full system modeling and simulation [114-117];
- Techniques to determine tag location [118-121];
- Multistatic reader antenna configurations [122];
- Novel portal and conveyor belt solutions [123].

We believe that these and other forthcoming developments open a plethora of new research issues and challenges in antennas and propagation for RFID systems of the future.

ACKNOWLEDGEMENTS

ABBREVIATIONS

BAP	–	Battery Assisted Passive
CW	–	Continuous Wave
DC	–	Direct Current
EIRP	–	Equivalent Isotropic Radiated Power
EPC	–	Electronic Product Code
EM	–	Electromagnetic
EMI	–	Electromagnetic Interference
Gen2	–	Class 1 Generation 2 RFID standard
HF	–	High Frequency
IC	–	Integrated Circuit
LHCP	–	Left Hand Circular Polarization
NFC	–	Near Field Communication
RCS	–	Radar Cross Section
RF	–	Radio Frequency
RFID	–	Radio Frequency Identification
RHCP	–	Right Hand Circular Polarization
RMS	–	Root Mean Square
Rx	–	Receive
SNR	–	Signal to Noise Ratio
TEM	–	Transverse Electromagnetic
Tx	–	Transmit
UHF	–	Ultra High Frequency

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