RFID Tag Characterization in a GHz Transverse Electromagnetic Cell

Sidney K. D’Mello, Divya Choudhary, Srikant Chari, James Markham, and Lee McCauley

Abstract—This paper presents results from a study that attempted to characterize the performance of RFID tags in a GHz Transverse Electromagnetic (GTEM) cell in which an approximately constant electro magnetic (EM) field potentially free of any extraneous interference was maintained. Performance of four commercially available RFID tags manufactured by different vendors was characterized on the basis of horizontal directivity, vertical directivity, sensitivity, and frequency characteristics.

Index Terms—RFID, reliability, directivity, GTEM

I. INTRODUCTION

Radio frequency identification (RFID) technology is on the forefront of many areas of interest to business, military, medical, middleware, healthcare, and educational institutions [1]-[6]. Though, once proclaimed to be the next generation barcode technology, the initial industry expectation and marketing hype has been subdued in light of critical challenges involved with widespread adoption of this technology. At the crux of the problems lies the financial overhead associated with the technology [7]. Current financial trends indicate that a tag, when purchased in bulk (> 1 million units), can cost about 13 cents [8]. This cost structure reflects a significant increase when compared to current working alternatives, i.e. barcodes which are virtually free. The next major hindrances to widespread RFID acceptance are the security and privacy issues that afflict the technology [9] – [10]. Fortunately, security has been the focus of much of the ongoing research within the RFID community and innovative solutions to alleviate some of the security challenges have been proposed [10] – [13].

The third critical challenges that hinder widespread use and acceptance of RFID technology are the substantive reliability issues involved in reading from and writing to remote RFID tags (or transponders). While the technologies involved in the development of RFID systems such as antenna design, RF-signal attenuation, etc, have been well studied, additional issues arise when a comprehensive systems consisting of tags and reader are deployed in real world settings. These include reader collisions when signals mutually collide [14], signal attenuation issues when tags are far away from a reader, and other environmental factors such as the presence of metallic components (desks, chairs, or studs in a wall), cell phones or cordless phones, computer equipment, sprinkler systems, water sources, and people. Other issues that arise in the deployment of RFID systems involve the location of the reader, the relative position of the RFID tags from the reader source, and the orientation of the tags [15]-[20].

When coupled with the existing financial and social challenges associated with RFID technology, the performance issues could ultimately settle the fate of the technology. This in turn has led to rapid development of RFID solutions to eliminate some of the crippling problems [21] – [26].

Although widely acknowledged as a critical avenue of research, the literature on detailed performance evaluations of RFID technologies in realistic settings is more sparse and scattered. As a first step towards this goal, it is important to first calibrate the behavior of RFID tags in environments free of external electromagnetic (EM) interference, in order to establish a suitable performance baseline. Therefore, as an initial step in a larger project that attempts to systematically evaluate the effects of real world factors on the readability of RFID tags, this paper describes a study that systematically attempts to characterize the performance of several commercial RFID tags in a controlled environment. We utilized a Radio Frequency (RF) chamber as a test facility to study the reliability associated with reading RFID tags with no ambient electro-magnetic fields other than the source of interest.

The motivation behind this study was to obtain a characterization of a variety of RFID tags within the closed environment of an RF chamber. In particular we were interested in exploring the effect that the characteristics of the source signal and the tag orientation have on the associated read error rates. The signal characteristics are composed of two variables, namely the frequency of the signal and the signal strength with the latter being measured as the degree of attenuation of the signal (i.e. no attenuation, strongest signal). Frequency was investigated in order to determine the optimal set of frequencies for each tag type. This information could be used to reengineer tag querying algorithms. The motivation behind
varying the attenuation of the signal was to simulate distance between the tag and the reader. The orientation of the tags was manipulated by individually rotating the tags along a horizontal and vertical axis. Understanding the performance of RFID tags under varying orientations is critical for real world applications because it is impossible to prespecify the orientation of a tag. In essence, tags should be orientation-invariant, i.e. readable at all orientations.

The study described in this paper attempted to systematically vary each of these parameters in order to evaluate their impact on tag performance, i.e. error rates associated with reading tags.

II. EXPERIMENTAL SETUP

A. Apparatus

The equipment used for this study consisted of a GHz Transverse Electromagnetic (GTEM) Cell, an Alien™ 9780 RFID scanner, several RFID tags, a customized vertically rotatable mount, and a host computer. These are briefly described below.

1) GTEM Cell: The RF chamber was a GHz Transverse Electromagnetic (GTEM) Cell, which is a radiated immunity and emission test facility that reduces the impact of the ambient electromagnetic environment. It is a pyramidaly tapered, doubly terminated section of 50 Ω transmission line (See Figure 1). At the input, a normal 50 Ω coaxial line is physically transformed into a rectangular cross-section. The central conductor (septum) of the transmission line is flat and wide. The septum, when driven by a signal source, produces a reasonably sized region of a nominally uniform electric field. The septum is physically terminated in a 50 Ω resistive array. In accordance to the theory of reciprocity, radiated immunity testing can be performed in the GTEM cell. This is an important factor since the GTEM antenna was used as both the transmitting and receiving antenna for the RFID reader.

Fig. 1. GTEM Cell

The GTEM cell was equipped with an octagonal turntable upon which the equipment under test (RFID tags in this case) can be securely mounted. The table top could be automatically rotated by use of an external controller with respect to an azimuthal (horizontal rotation) and an inclined orthogonal (45°) axis. As shown in Figure 2. In all experimental conditions, the tags were mounted on Styrofoam blocks and placed at the center of the turntable.

Fig. 2. Tag in GTEM cell at base position (no rotation)

2) Alien™ 9780 RFID Scanner: An Alien™ 9780 RFID scanner was used as the signal source in the RF chamber. The scanner sweeps frequencies over a 902 -928 MHz range in the ISM band. However, since one of the goals of this project was to investigate the frequency characteristics of the various tags, the scanner was modified so that instead of automatically sweeping through all frequencies, a target frequency for transmission and reception of the signal could be set. Therefore, in the subsequent analyses we test tag reliability by incrementally setting the frequency over the 902 – 927 MHz range.

The scanner is equipped with an internal attenuator that can cause a 0 dBm to 16 dBm attenuation of its output signal. With no attenuation applied, the scanner transmits with a signal strength of 30 dBm. The scanner is also equipped with an external ALR-9610-BC antenna. The ALR-9610-BC is a circular-polarized antenna so it radiates energy in a symmetric manner. However, in the subsequent analyses the antenna of the GTEM cell was used for wireless communication with the tags bypassing the ALR-9610-BC.

3) RFID Tags: Four EPC UFH Class 1 tags were used for the experiments. Three of the tags were commercially available RFID tags manufactured by Avery Dennison® (AD-610 and AD-410) and Alien Technology® (AL-9338-02). The fourth was a prototype tag developed by an unspecified vendor. Throughout this report these tags will be designated as Tag-A for the unspecified tag, Tag-B for the AD-610, Tag-C for the AL-9338-02, and Tag-D for the AD-410 tag.

4) Vertically Rotatable Mount: As mentioned above the turntable in the GTEM was designed to rotate horizontally and along an inclined orthogonal (45°). However, it did not possess the capability of rotating vertically which is an important requirement for the orientation analyses. In order to alleviate this problem we designed and manufactured a vertically rotatable mount that could be manually positioned to a predefined angle. The mount was designed such that a Styrofoam block that hosted a tag could be affixed to it and the entire block could be manually rotated in 5 degree increments. The materials used to construct the mount were Plexiglas and the various components were fused together with nylon bolts, hex nuts, and washers in order to minimize sources of metallic interference. Figure 3 shows a sample tag secured on the vertical mount and rotated
5) Host Computer: A Dell PC was used as a host computer that was connected to the turntable controller and a spectrum analyzer with a National Instruments™ USB-GPIB adapter. It was also connected to the RFID scanner through an Ethernet connection. The host computer also connected to the modified scanner in order to control the frequency via a parallel port. The scanner was manually controlled by the Alien Gateway™ software version 3.3 installed on the host computer. An Application Programming Interface (API) written in the Java™ programming language was used for automated communication with the scanner. The scanner was configured to read all class 1 tags (this includes 0 and 0+ tags) and its acquire mode was set to global scroll which involves sending out a command to quickly search for the nearest tag as opposed to finding all tags within the range of the reader (called the inventory mode) [27].

B. Procedure

The RFID tag under test was mounted on a Styrofoam block and placed on the center of the turntable (Figure 4). The rotations across the horizontal and vertical axes were independent of each other. Specifically, when the tag was being horizontally rotated, its vertical angle was set to 0° and vice versa.

Table I presents a depiction of the various parameters used in the study. Separate runs were conducted for the horizontal and vertical orientations. For each orientation of the tag on the turntable, for each attenuation setting, and for each frequency, 20 read attempts were performed. Error rates were then evaluated on the basis of the number of times the tag responded to the 20 read attempts. The measurement procedure can be annotated as:

1. The host computer positions the turntable by communicating with the table manipulator for horizontal rotations. (The experimenter manually positions the vertically rotatable mount for vertical rotations).
2. The host computer sends a message to the scanner to initiate polling for tags.
3. The scanner transmits a signal through the main antenna in the GTEM cell.
4. The RFID tag under test receives the signal.
5. The signal is broadcasted back to the antenna.
6. The received signal is relayed to the scanner.
7. The scanner transmits whether the read was successful or not back to the host computer.
8. The host computer logs the result of the read attempt into a log file for offline analyses.

Table I

<table>
<thead>
<tr>
<th>Variable</th>
<th>Initial Value</th>
<th>Final Value</th>
<th>Increment</th>
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<tr>
<td>Attenuation (dBm)</td>
<td>0</td>
<td>12</td>
<td>0.5</td>
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<tr>
<td>Frequency (MHz)</td>
<td>903</td>
<td>927</td>
<td>1</td>
</tr>
<tr>
<td>Horizontal Rotation (degrees)</td>
<td>0</td>
<td>330</td>
<td>30</td>
</tr>
<tr>
<td>Vertical Rotation (degrees)</td>
<td>0</td>
<td>330</td>
<td>30, 100</td>
</tr>
</tbody>
</table>

*For vertical directivity a preliminary analysis resulted in expanding the scope to include the following angles: 40, 50, 130, 140, 220, 230, 310, and 320.

III. Results

The four tag types were characterized on the basis of horizontal and vertical directivity, sensitivity, and their frequency characteristics. The analyses proceeded by first computing an error rate for each read attempt for each tag. The error rate was computed as the ratio of the number of failures to the number of read attempts (N = 20). Therefore, the error rate ranges from 0 (perfect read) to 1 (complete failure).

For each orientation of the tag in the chamber, the modified scanner was used to incrementally set the frequency of the output signal across the 903-927 MHz range. Additionally, for each frequency setting the output signal was attenuated across a 0 – 12 dBm range with increments of 0.5 dBm.

For each frequency, tag performance was calculated on the basis of the amount of attenuation required to obtain an error-rate of approximately 0.5. Therefore, with this performance metric, higher attenuation rates imply good readability whereas lower attenuation rates are indicative of poor readability. This procedure formed the basis for computing directivity and frequency characteristics of the RFID tags.

A. Horizontal Directivity

Figure 5 presents assessments of the horizontal directivity. It should also be noted that the data collection procedure was replicated for 3 individual tags from each of the four tag types (Tag-A, Tag-B, Tag-C, and Tag-D) yielding 12 runs in all. The results presented for each tag type have been averaged over the 3 individual tags. In Figure 5 we average across the 903-927 MHz frequency set.
A number of general conclusions can be drawn on the basis of the mean horizontal directivity (Figure 5). In particular, performance of the four tags can be ordered as Tag-B, Tag-A, Tag-D, and Tag-C. Additionally, although performance of each tag type varies, a consistent trend in horizontal directivity emerges. Specifically, the best performance was obtained for the 0° and 180° orientations in which it takes about a 5 dBm attenuation to cause a 0.5 reduction in performance (for Tags A and B). The horizontal directivity was lower across the 0°-120° and 240°-330° ranges. The four tag types appear to have a 120° blind spot between the 120°-180° and the 180°-240° ranges where they did not respond at all.

B. Vertical Directivity

Figure 6 depicts the mean vertical directivity. The results indicate a change in tag performance when compared to the horizontal directivity in that Tag-C outperforms Tag-D. Additionally, although Tag-A typically outperforms Tag-B, we observe Tag-B exhibiting a superior performance when rotated to the angles of 50°, 130°, 230°, and 320°. Similar to the results for the horizontal directivity, a consistent pattern in terms of vertical directivity across all four tag types is observed. In particular, performance is the best for the 0° and 180° orientations and moderate for the 30°, 150°, 210°, and 330° orientations. Performance then sharply drops across the 30°-50°, 130°-150°, 210°-230°, and 310°-330° ranges. Finally, when the tags are extensively rotated (50°-130° and 230°-310°) performance drops to 0 as noted by the fact that a non-attenuated signal produces no valid reads (an error rate of 1).

C. Frequency Characteristics

The frequency characteristics of each tag were investigated in a similar manner as the directivity patterns. The amount of attenuation required to produce a 0.5 error rate calculated for each frequency was used as the metric to evaluate performance. However, the measurements used to evaluate the frequency characteristic of each tag were performed when the turntable was not rotated (0° horizontal and 0° vertical). Additionally, 5 individual tags of each type were used to evaluate the frequency characteristics with the results for each tag type being averaged across the individual tags. Figure 7 graphically depicts the frequency characteristics of the four tag types. We note that performance of tags A and B are on par and quantitatively higher than tags C and D which are similar to each other. When aggregated across the 4 tag types a general pattern of performance with respect to the different frequency values emerged. In particular, performance is higher for the lower and higher frequency ranges but drastically drops across the middle frequencies weakly resembling an asymmetric inverted
U pattern. A regression analysis revealed that a 6 degree polynomial was moderately successful ($R^2 = .474$) in capturing the relationship between tag performance (i.e. signal attenuation required to achieve a 0.5 error rate) and signal frequency.

**D. Sensitivity**

The sensitivity for a tag provides an assessment of the error rate as a function of signal attenuation. Here we assume that the attenuation approximates the distance between the tag and the signal source (the transmitting antenna). Similar to the frequency characteristics described above the sensitivity analysis involved assessing the error rates associated with 5 individual tags of each type without rotating the turntable (0° horizontal and 0° vertical). On the basis of the sensitivity of each tag depicted in Figure 8 (which has been averaged across the 5 individual tags) we conclude that the sensitivity of Tag-A and Tag-B are on par and quantitatively higher than that of tags C and D which are highly similar with each other. The results indicate that all tags break down and yield error rates of 1 when the level of attenuation exceeds 8 or 9 dBm.

There appears to be a linear relationship between the attenuation of the signal and the error rate of the tags. When averaged across the four tag types, a linear regression analysis yielded an excellent fit to the data with $R^2 = .94$.

**IV. FUTURE WORK**

Our research agenda incorporates two additional studies that will attempt to replicate the measurements of this study in an open environment i.e. a typical office environment. The use of an office room instead of a GTEM cell will endow us with the ability to increase the scope of the study. In the current study the tag was placed at only one position in the chamber, i.e. at the center of the turntable. However, in an office room the number of potential locations in which a tag may be placed is much larger. In theory, a tag can be placed at any location in the room. Therefore, due to the increased scope of measurements in the next study we have designed, manufactured, and installed an industrial robotic system to automatically position a measurement device (antenna or RFID tag) anywhere in the room. The system will then be used to automate the measuring process by reducing the overall time needed to complete the requisite data collection. It will also serve a secondary goal of minimizing the amount of human error that could be expected if tags were manually positioned in the test room.

**V. CONCLUSION**

The increased integration of RFID technology into products designed for use in typical office environments highlight a number of technical, logistic, and usability issues. While several have been quick to extoll the virtues of RFID technology, a systematic investigation into the performance and usability issues that occur in real world environments is lacking. While the research reported in this paper did not explicitly tackle these issues it signifies a preliminary step into gauging the reliability and overall feasibility of incorporating RFID technology in various environments. By evaluating the reliability in reading RFID tags in a controlled environment that was presumably devoid of extraneous interference we hope to have established a suitable performance baseline.

We acknowledge that the research reported here is not without limitations. Some of the issues that might reduce the generalizability of the results are that only a handful of different RFID tags were used. Another issue of potential concern lies in the fact that only one type of RFID scanner was used and its antenna was only placed at a single location in the test room.

A number of extensions can be made to the study to increase its generalizability. These include evaluating different types of tags such as tags from the Avery-Dennison (AD) series. Another useful set of experiments would involve using different types of RFID scanners. In essence our results indicated that the AD-610 tag (Tag-B) performed the best followed by the unspecified tag (Tag-A). Performance of the AL-9008-02 tag (Tag-C) and the AD-410 tag (Tag-D) were on par and quantitatively lower than tags A and B. The next set of experiments in the office room will attempt to investigate whether these performance patterns replicate in addition to determining how these tags perform when compared to additional commercially available RFID tags.

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REFERENCES


