Determining a Better Metric for RFID Performance in Environments with Varying Noise Levels

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Abstract— **Often users wish to maximize the range of a passive RFID system. At the furthest extent of their range the signal between tag and reader will be at the weakest level which the reader can detect. It is desirable to know how close a system is to operating at this level, since the data being transmitted will be increasingly susceptible to small increases in the channel noise. This paper examines two techniques to survey an RFID system's performance, and investigates two sampled environments: a large bare room, and a manufacturing facility with extensive fixturing. It seeks to 1) identify a useful metric for measuring the performance of an RFID tag and reader in a given configuration and 2) evaluate methods for surveying this performance across a space to be used for an RFID system deployment.**

I. Introduction

There is increasing interest in implementing RFID systems in industry to augment or replace barcodes for data acquisition in the supply chain. While this transition promises great advantages, it is not without difficulty for many implementors. One difficulty posed by RFID is that of developing an intuition for how it performs. Many current sensors perform their measurement using a medium which humans can easily sense: it is easy to see if a break-beam is aligned correctly, or if a barcode scanner is aimed at the proper barcode, since there is a visible light which illuminates the target. A tactile sensor will make a sound as it engages or can be wired to light a signal. In both of these examples, the part of the process which the installer can control is simple to understand: with enough force on the sensor a switch is tripped and a signal made, or the when the laser is unimpeded, the barcode is read. Understanding RFID is made more difficult because the tag and reader communicate with radio waves, which are invisible to our senses. The only readily available feedback that can be seen is the result from the reader: a read (or no read), with little information about the process which led to it. Without specialized equipment it is not possible to make even a qualitative judgement about the strength of the received signal to see if an RFID reader is receiving a strong consistent signal from the tags, or an intermittent weak one. This can make it difficult to ensure that an RFID system is installed in a robust configuration and not operating too close to the noise floor. As a way to alleviate this shortcoming, this paper provides a detailed picture of the behavior of RFID systems in common environments, and provides visual representations of the reader field which can be used to help with installations. It also evaluates the use of read rate as a measure of signal quality by comparing it with another method.

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When installing and using an RFID system it is desirable to know how it will perform in that working environment. When trying to achieve optimum performance from the reader, it is helpful to know where in the workspace tags will be reliably read. This is not always easy to calculate. The propagation of radio waves can be affected by the contents of a room, its shape, and its physical makeup. It is also possible for electromagnetic noise near to the system to interfere with its operation [1].

This paper presents work to identify a suitable metric for RFID read quality and to empirically obtain a representation of the read field for a given RFID tag and reader. A useful by-product of this work was the development of a system to assess these data which can form a foundation for future similar experiments.

II. Requirements

Measuring the performance of an RFID system requires recording a measurement of the read quality at a representative group of points. A common test for the quality of an RFID configuration is to see how quickly a tag can be read and to calculate a read rate. Previous experiments [2], [3], [4] which have characterized RFID read fields have tested one tag position at a time. Some such experiments have used a grid marked out on the floor at set intervals, and an adjustable stand. The tag on the stand is placed on the grid, a reading is taken, and the stand is moved. In this manner all of the points can be measured. There is some error associated with the placement of the tag at each location, since the stand would need to be adjusted for each successive point.

In order to reduce this placement error in this experiment, the tags were attached to a large vertical frame, allowing a number of them to be moved at once (Fig. 2). This meant that the spacing between data points was uniform in two dimensions, and the error was reduced in the third dimension as compared with the single tag method. Since the relative positions of the tags were fixed, any errors in the alignment of the two endpoints of the array were divided across all of the tags. The placement error e of a given tag at position d in Fig. 1 is determined by the errors in placing the two ends of the array δ_1 and δ_2, and including an error $e_p = .5$cm due to movement of the plastic sheeting to which the tags were attached:

$$e = \delta_1 - \frac{d}{l}(\delta_1 - \delta_2) + e_p \tag{1}$$

$$e_{rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} e_i^2} \qquad (2)$$

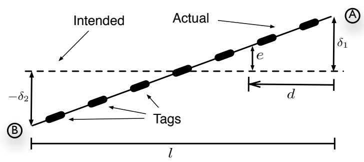


Fig. 1. The placement error due to an array, a plan view of Fig. 2.

The frame (Fig. 2) was made of wood, with thin plastic sheeting stretched over the front to form a smooth surface for attaching the tags. No metal was used in its construction to prevent reflections. It has been shown that wood can have a negative effect on RFID performance, so the tags were not installed within 10cm of the edges of the frame [5]. The main face measured 3m square and with tags at 20cm spacing this made a 14x14 grid.

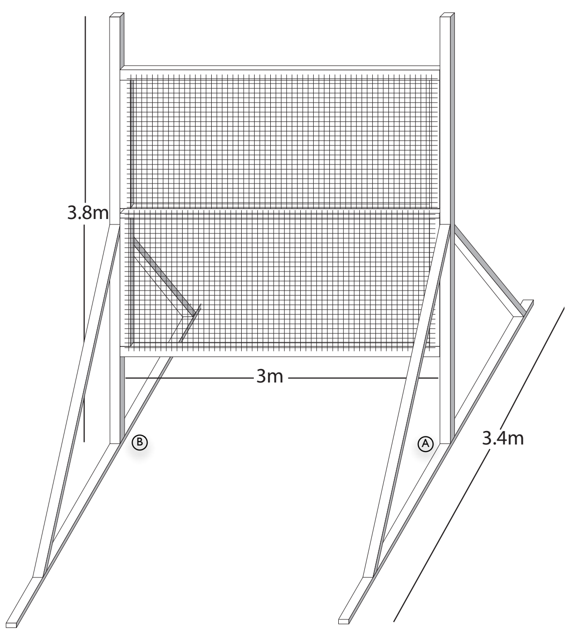


Fig. 2. The frame which supported the grid of tags. It was constructed entirely of wood, with plastic mesh stretched over the frames for rigidity and a sheet of thin plastic taped on top of that to accurately attach the tags to.

A. Transition Time

The use of the frame also meant that the experiment could be conducted more quickly than if the tags were moved individually. If we assume that moving the stand to its new location takes 15 seconds, it would take 10.5 hours just to move the tag to each point in the area described here using the stand method, without even taking readings. The total time taken for the experiment is determined by the time it takes to read each tag (the read time) and the time to move to the next tag (the transition time).

1) Multipath Interference: The tag array introduced the possibility of interference from adjacent tags, either parasitic effects or as sources of reflection. When the tags are not active they could reflect back a fraction of any signal incident upon them and this reflected signal would then combine with the original signal, possibly out of phase. This effect is illustrated in Fig. 3.

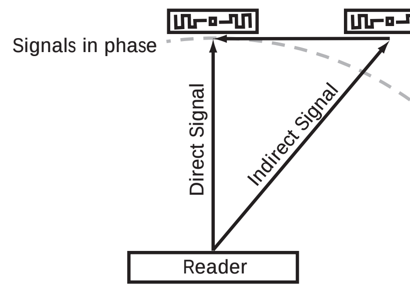


Fig. 3. Phase differences caused by reflections. When the reflected and direct signals meet they are out of phase, and can either add to or subtract from each other, depending on the phase difference.

2) Accounting for Multiple Tags: Since more than one tag was used it was necessary to control for variations in tag strength. A batch of 220 tags was available, of which only 196 were used. The tags were tested at a constant power and their read rates measured. This constant power level was provided by holding the tags in a consistent position relative to the reader. Each tag was held in a wooden jig 1m away from the center of the antenna and interrogated 40 times. The average read rates over these reads were then recorded. When the tags were installed on the array, those with the highest read rates were used.

B. Read Time

The total read time is affected by the number of times the reader interrogates a tag. A lower number speeds up the gathering, but (up to a point) a larger number produces a more stable overall read rate.

The readers used in this testing use an anti-collision algorithm to handle the presence of more than one tag in the read field. The protocol is a part of the EPCglobal Class 1 version 1 specification [6]. It uses the ID of each tag (the 64 bits of the EPC) to uniquely identify and then address it. The reader first broadcasts to all the tags asking for their ID. If more than one replies, it requests a subset of the tags by using a 3 bit mask, which orders only tags whose IDs begin with the given string of bits to respond. Whenever it encounters more than one tag transmitting at once, another 3 bits are added to the mask and the process is repeated. By this method eventually the reader has traversed a tree of all possible tags and identified each tag in the read range.

When the anti-collision algorithm is used, the reader traverses this tree to interrogate each tag. Since they might fall at different levels in the tree, the amount of time necessary to interrogate the various tags could differ (Fig. 4). These differences in read times would affect the overall read rate, which would add an additional source of error to

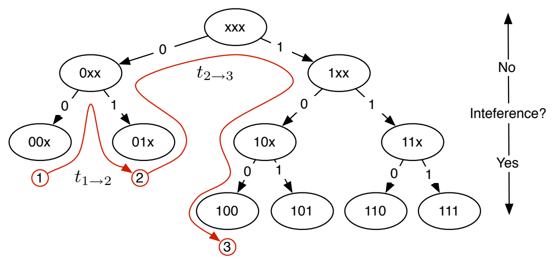


Fig. 4. The anti-collision system. Depending on the tags present in the space, the time taken to traverse the binary tree can vary. Here $t_{1\to 2}$ is faster than $t_{2\to 3}$

the readings. In order to guarantee a uniform tree-traversing time for each tag it would be necessary to place each at the same level of the tree, i.e. to assign EPCs in such a way that the processing times would be equal.

Because of the added processing time which comes with using the anti-collision protocol and the possibility for varying transition times, it was decided to interrogate tags one by one. This allowed the reader to be run without the anti-collision processing, interrogating a specific tag as quickly as possible.

III. Method

Experiments were conducted in two different locations to plot the performance of a specific antenna and tag combination in a large number of possible positions. The equipment used was manufactured by Alien Technology. Their ALR-9750 reader was used with a circularly polarized antenna, operating under a 915MHz test license at the University of Cambridge. This antenna provides orientation independence in the plane parallel to the reader, and so is a popular choice for scenarios where the tag's orientation cannot be guaranteed. Although a part number was not available, it is believed to be manufactured by Cushcraft, and their S9028PC is the antenna most similar in specifications and packaging. The tags were the Alien ALL-9340, 98.2 x 12.3 mm, and used their Omega revision silicon (Fig. 5).

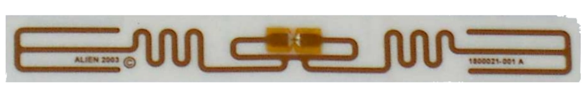


Fig. 5. The Alien Technologies ALL-9340 tag

A. Choosing a Performance Metric

The measurements made of the read field needed to demonstrate the likelihood of a tag being read at that position. The interrogation of a tag consists of a predictable sequence of commands and responses, and in an ideal environment with no errors or need for retransmission this sequence should be executed in an unvarying amount of time [6]. A retransmission would extend the interrogation time, and a proper metric would account for this variation. The likelihood of a read relates to the strength of the EM field at the tag, at least at the most basic level (below some threshold there will not be sufficient incident power on the tag to scatter back to the reader), and so measuring the field strength and extrapolating the reader's performance was a possibility. The tag's read likelihood relative to power levels was not known, however, so a power level would not be sufficient to predict the likelihood of a tag being read.

Interference present in the environment can hinder or prevent communication between the tag and reader. More noise will make errors more likely, and will increase the total time taken to complete an interrogation. Thus the amount of time needed to complete a read is an indicator of the reliability of subsequent reads in a given tag-reader configuration. So the read rate over a number of reads, which the Alien reader provides automatically, was taken to measure performance. The tag would be placed in position, interrogated 40 times in succession, and the average read rate recorded.

B. Evaluating Antenna Response

Typically antenna designs are evaluated in complete isolation in an anechoic chamber to develop a map of their gain in various directions. These maps are made from a series of individual readings taken at points around the antenna. Since there are no external reflections or noise sources in this scenario the readings can be assumed to be free from errors [7]. The purpose of this experiment was to produce a similar map, but of an antenna's performance in an existing environment when used with an RFID system.

To produce this, it was necessary to evaluate the performance of the system in a repeatable manner for each unique tag position relative to the antenna. Ideally this would include all of the points where the tag could be read, and a border area without any reads large enough to be reliably considered the furthest extent of the system's range. Preliminary testing indicated that the system would have a range of at least 6m and that a cross-sectional area 3m x 3m would need to be measured along this range. In order to keep the number of measurements tractable, it was decided to measure system performance every 20cm over the 6 x 3 x 3m area, for a total of 7,936 points.

C. Testing Environments

The first environment used was a large indoor hall, with a floor measuring 7m square with 4m ceilings. The floor was a wooden parquet laid on top of cement. Metal beams with .6m square cross-sections ran along the ceiling perpendicular to the face of the tag frame on 3m centers (Fig. 6). The antenna was mounted on a metal stepladder, which was positioned mid-way between the two ceiling beams. The experiment was oriented so that these beams were parallel to the antenna-tag vector, so that any influence they exerted would be consistent along all of the slices. The antenna center was 2m off the floor, directly centered on the central tag on the frame. Two parallel lines were marked on either side of the floor at 20cm intervals for positioning the legs of the stand.

The second environment was the Automation Lab at the Cambridge University Institute for Manufacturing (Fig. 7). This space is a small manufacturing facility with motorized shuttles running on metal tracks, 3 industrial robot arms, and a large quantity of metal fixturing. One of the robots is suspended from a solid steel beam which runs the length of the room, 2.5m off the floor. The entire space is surrounded by a aluminum-framed clear plastic safety fence. The testing was conducted in a space 1m above the shuttle track and with 1m of free space on either side between the steel support beam for the moving robot arm and the safety fence (Fig. 7).

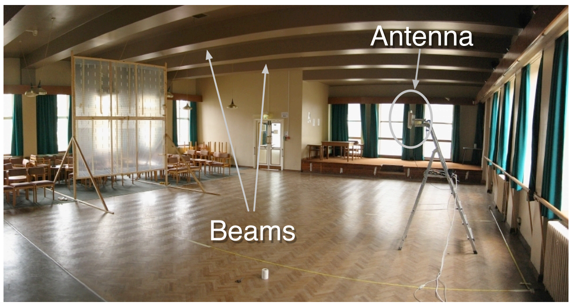


Fig. 6. The first testing space

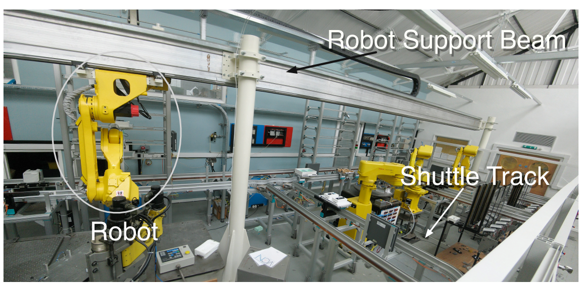


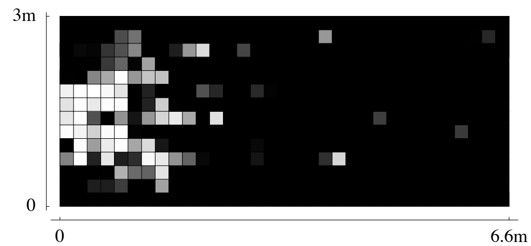
Fig. 7. The second testing space

IV. Data Gathering

A. First Experiment

For the first experiment, the wooden frame carrying the tag grid was set up in the testing area as shown in Fig. 6. The reader was controlled by a Perl script on a laptop, which was connected to the reader by a cross-over ethernet cable. Once the frame was in place, the script sequentially interrogated each tag 9 times: 3 times at each of three frequencies (channels 43, 44, and 45 as designated by the reader). After each tag had been interrogated, the frame was moved 20cm and the measurements repeated, so that a data set was built up over the testing volume at 20cm increments in each direction.

The three channels were measured individually in order to provide finer-grained information about the frequency response of the environment. Fig. 8 shows congruent slices of data from the three different frequencies (taken vertically, perpendicular to the reader face), and then a composite of the three. While there are some points which are not shared by all three channels, and are thus colored in the composite plots, it is difficult to deduce a pattern from them.



(a) Channel 43: 919.8 MHz

(b) Range across channels

Fig. 8. (a) A horizontal (plane b in Fig. 13) slice through the data and (b) the size of the range of values seen across the three channels

The baseline read rates recorded before the tags were attached to the frame were used to normalize the data. Each initial rate was divided by the overall average of the population used in the experiment. The readings taken in the experiment were then divided by this ratio to normalize them. The result of the normalization is illustrated in Fig. 9 by two slices of data taken in the plane parallel to the reader and the tag frame.

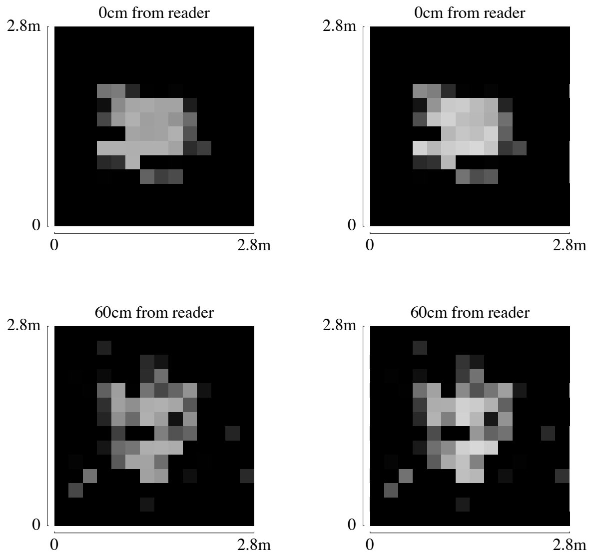
1) Data: Fig. 10(c) shows a representative horizontal slice through the collected data, arranged spatially with read rate indicated by brightness. As the tags reflect back incident power they can be modeled with the radar equation, which relates the power received back at the reader P_r to the range to the tag R

$$P_r = \frac{P_t G_t G_r \sigma \lambda^2}{(4\pi)^3 R^4} \tag{3}$$

where P_t is the power transmitted by the reader, G_t and G_r are the gains of the transmit and receive antennas, σ is the target cross-section, a constant which in this case encapsulates the efficiency of the tag antenna and the fraction of incident power which it re-radiates, and λ is the wavelength. The Alien reader uses one antenna for transmit and receive, so $G_r \equiv G_t$ and is invariant. The variation of λ between channels can be neglected, and σ will be taken as a constant. The equation can now be written like this

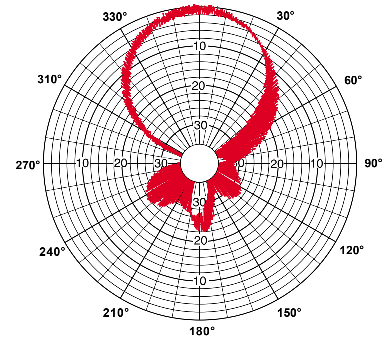
$$P_r = \frac{KG^2 P_t}{R^4}, \text{ where } K = \frac{\sigma\lambda^2}{(4\pi)^3} = 165 \cdot 10^{-6}\sigma \tag{4}$$

[8]. In order to predict read events, a threshold must be added to the model. The reader can only read a tag when its

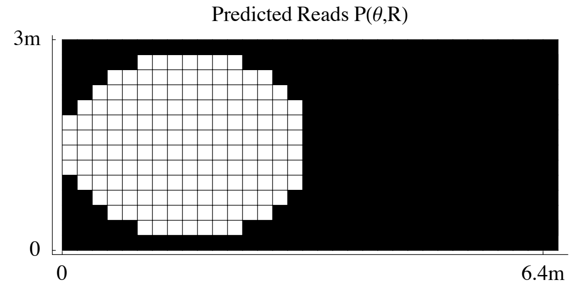


(a) Raw data from different tags (b) Normalized data

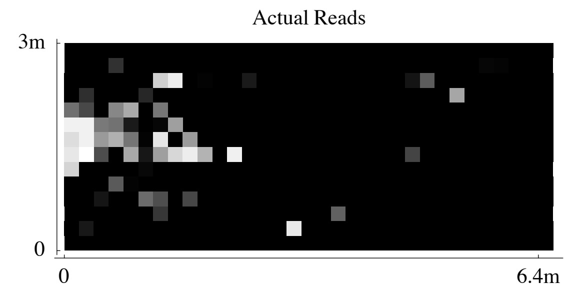
Fig. 9. The effect of normalization on the data. Slices taken parallel to the face of the reader at increasing distances.



(a) Cushcraft S9028PC radiation pattern



(b) Predicted data



(c) Actual data collected

Fig. 10. Theoretical and actual response

power is above the reader's sensitivity P_{read}, so the model will actually be

$$\text{Tag read} = \begin{cases} 1 & P_r > P_{read} \\ 0 & P_r < P_{read} \end{cases} \tag{5}$$

In the actual environment there is a noise level and a read event is dependent on the signal level being higher than the noise, which is modeled by a Gaussian random variable. So

$$P(\text{read}) = P(P_r > N), \text{ where } N \textit{ Gaussian} \tag{6}$$

The gain of the antenna is determined from the antenna plot given in the data sheet. Only the azimuthal ($G = G(\theta)$) data is given, so accurate predictions can only be made for $\phi = 0°$ [9].

Fig. 10(b) shows the theoretical power received at the reader for a tag positioned at each point around the space. Fig. 10(c) shows the actual measured data. The predicted and actual data are obviously not well correlated.

2) Discussion: This theoretical derivation assumes that the medium through which the radio waves propagate (the air) is isotropic. If it is not, and that were accounted for, it would change the overall shape of the plot but likely not explain the strong outlier points. Because different tags were used, all the read rates had to be normalized. Initial read rates were recorded at a reference distance to determine each tag's maximum rate. The data plotted are the recorded read rate divided by the maximum measured read rate for that tag. This normalization should account for variations in inherent tag performance, but not external variations. It is possible that a different normalization technique would have produced different results, but unlikely that it would remove the outliers completely. The outliers might be caused by constructive reflections from surrounding materials or conversely other points around them could be masked somehow, making these points appear as outliers. There is also the possibility that the tags do no perform repeatably, a fact which would not have been picked up by the initial screening performed for normalization. To have this sort of variability in a solid-state device is very unusual, however, and would most likely be due to a mechanical fault, such as at the connection between chip and antenna. An intermittent connection like this in an RF device would affect its performance, even when it was connected properly, so the initial screening would have identified the tag as having a low read rate.

3) Future Improvements: The initial vetting of tags was not adequate to fully determine their performance of the tags. Future experiments would do well to include multiple reader-tag distance in their tests, and to examine the falloff of each tag, in addition to whether it is read or not at a given distance.

B. Second Experiment

The second experiment was performed in a different environment and with a different method. The lab setting was intended to be typical of a manufacturing facility, with its many physical obstructions and potential sources of electromagnetic interference. In addition, the installed industrial robot arms could be used to accurately and repeatably position the tags. Using the robot arm, which can be directed to positions with sub-millimeter accuracy [10], provided much higher placement accuracy and precision than was possible in the previous experiment. The robot, which can move accurately between points at speeds of over 1m/s, also greatly reduces the transition time, making it feasible to collect point data with a single tag rather than using an array.

The unobstructed space in which the tags could be moved by the robot was not as large as it had been in the dance-hall. An attenuator was added between the antenna and the reader in order to reduce the power sent and received and therefore shorten the range. The same criteria were applied to the read area as in the first experiment: none of the points in the outermost positions should give successful reads. It was found that a 10dB attenuator was appropriate to achieve this. The use of the attenuator should only affect the G term in (4). To cover the smaller volume completely, the distance between points was reduced to 10cm.

1) Possible Downsides: While bringing accuracy and speed advantages to the data-gathering process, the robots also have some potential downsides. The steel from which the robots are constructed is conductive and reflects incident EM waves. The motors create EM radiation, although very little is probably in the 900MHz range. Both of these attributes could potentially disrupt the communication between the tag and reader. The lab was chosen partly because it had more potential for noise than the first environment, but this makes modeling more difficult.

A further complication is that the robot's geometry actually changes with each tag position, since the tag is attached to the arm. This means that there will be slight changes in the parts of the environment which might produce reflections from one tag position to another.

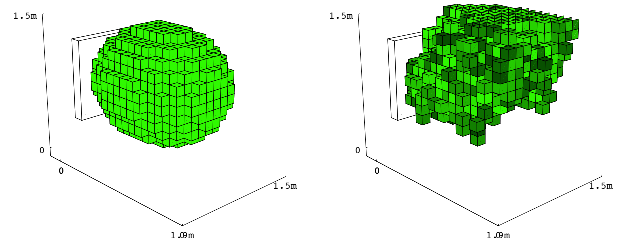
2) Data: These data show a much higher correlation with the modeled performance, as can be clearly seen in Fig. 11.

There are very few outliers, in contrast to the previous set. Since this environment had more potential sources of interference, particularly transients and rough scattering surfaces, it would be expected that it would produce data with more outliers and occasional points in positions which seem unlikely given the overall antenna pattern suggested by the data. However the distance from tag to reader is much less in this experiment, and at its furthest extent the tag is only 1m away from the reader instead of the 5m measured previously. The smaller range means that nulls caused by reflections in the environment will be relatively larger, compared with the total testing space, and so more consistent across the experiment. This could contribute to the uniformity of the result. The use of a single tag instead of a range of tags also removes another possible source of variation in the results.

This makes it likely that the the outliers are due more to the variation in tags used in the first experiment than to interference from the environment. This is discussed further in the next section.

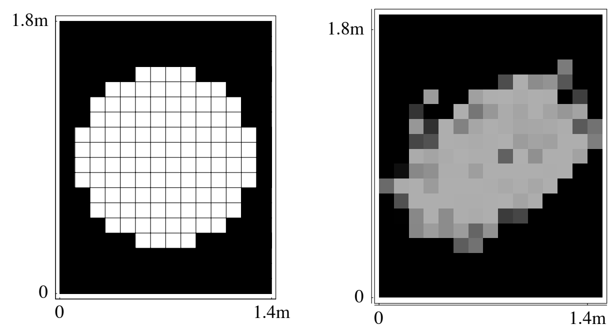
3) Discussion: Since a circularly-polarized antenna was used in the tests, it was expected that the resulting data would be roughly rotationally symmetric about the center of the antenna. It is surprising, therefore, to see the outward pull in the first and third quadrants of the antenna plane (Fig. 12, plane (c) in Fig. 13). If these are in fact distortions, that is, results caused by outside factors in the environment rather than by the inherent properties of the tag and reader, then there are some possible explanations:

- The robot has already been mentioned as a possible source of reflections. As it changes its geometry to place the tag in various positions in the xz plane it changes its profile to the reader, so that actually no two points measured in the plane feature exactly the same configuration. An attempt was made to minimize this effect as much as possible by using a .6m long end effector to keep the tag distant from the robot, but at the furthest extent of the robot (0,0 in these graphs) it was certainly closer to the center of the antenna field than at its shortest extent (14,14) and therefore strong signals were incident on its arm and potentially reflecting to cause interference at the tag. If this interference was constructive it would boost the apparent signal at points which, were it not for the robot, would not appear as strong. The opposite side of the plots should not see a similar effect, however, because the robot is even further



(a) Predicted data (b) Actual data

Fig. 11. Data for second experiment



(a) Predicted data (b) Actual data

Fig. 12. Slices of data 35cm from the reader

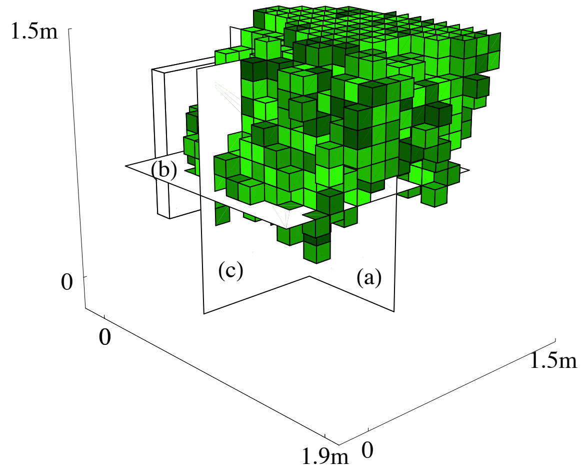


Fig. 13. The *xy* (b), *yz* (a), and *xz* (c) planes

away from the tag than the antenna. While it can provide some reflection it is unlikely to boost signals which are already weak and which would be receiving reflections from an even weaker area (where the robot is).

- The first experiment used multiple tags but tried to account for any variation in the population by normalizing the results. If this did not work then some of the results seen in the first experiment would be due to variation in the tag population, rather than the tag's location.
- It is possible that the antenna does not actually provide a symmetrical field, as was assumed, or the polarization of the antenna could be a factor. Circular antennas can have either a clockwise or anti-clockwise polarization while still keeping their rotation independence. An identical antenna of opposite polarity was not available to investigate this possibility.
- Finally the distortion could be due to constructive interference caused by the support beam for the robot, which runs perpendicular to the face of the antenna in the top corner of the first quadrant of these results.

V. Comparison of Data

The first dataset does not match the expected data very closely given the antenna plots taken from the Cushcraft datasheet [9] . This makes it very difficult to draw conclusions from a comparison of the first and second sets of data and, further, to make inferences about the second environment. The widely-dispersed results in the first set as compared with the second are due to a combination of three factors: reflected signals form the adjacent tags, a problem with the initial assessment of the tags and the subsequent normalizing of the data, a problem with the use read rate to compare the strength of the antenna field.

The adjacent tags could have provided more than the expected amount of interference, but they are well outside the first Fresnel zone at all but the farthest distances, so they should not have much reflective effect. The transition between near and far field for electrically small antennas is taken to be $r = \frac{\lambda}{2\pi} = 5.2$cm and for electrically large antennas $r = .62\sqrt{\frac{D^3}{\lambda}} = 34$cm [7]. The tags are 10cm long and cannot be considered entirely electrically small, but are also not clearly electrically large. The 20cm spacing ($.6\lambda$) puts them at least at the outer limits of the adjacent tags' near field, and so any interference should be minimal or non-existant.

The data were normalized based on a single reading at a fixed distance. This method assumed that while there might be variation in the actual numbers recorded for the various tags, the shape of their read rate vs. distance curves would be the same, so that the results could be normalized and produce a graph to simulate one made with a single tag. If the read rates don't fall off predictably across all of the tags, or if their variance is too high to discern a trend, then this method will not work. In this case it would be necessary to gather a large number of data points for each tag and use them to look up the expected read rate at a given distance when the tag was centered on the reader. By calculating the difference between looked-up and actual some conclusions could perhaps be drawn. Of course if the readings do not correlate with power (as a correlation with distance implies), then this method would not work.

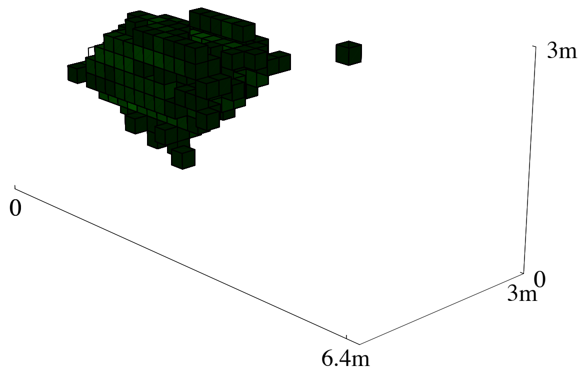
These results will prove useful in further experiments A premise of this experiment was that a reader's response to various tags could be used to predict its response to others. If this is not the case then the experiment cannot help to make these predictions. Fundamentally the tags react to the amount of power they receive and their backscattering is affected by the noise level in the transmission channel. There will therefore always be some relation to the power level, if only a binary one. Furthermore these are the only two factors which will affect the read rate (disregarding anti-collision issues) so with enough information mapping the read rate to the power level it should always be possible to create a chart of space using this technique. The question simply becomes one of precision.

The read rate was measured in both experiments, so it is not the sole explanation for the difference. However, it is possibly more susceptible to variations in signal level and it might be possible to use an improved metric.

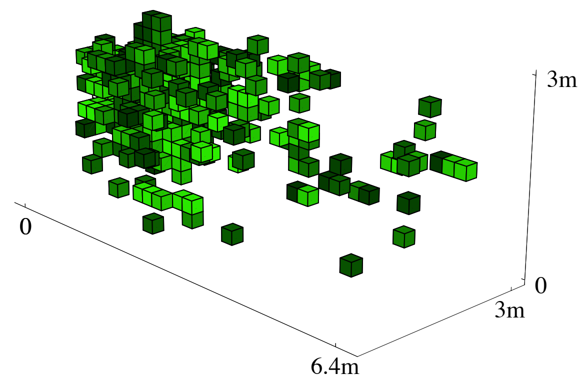
VI. Third Experiment

To further examine the read rate measurement, another experiment was performed in the same location as the first. Instead of using the read rate to measure the power level, a variable attenuator was inserted between the reader and its antenna. For each reading the attenuation was increased until the tag was not read, and this attenuation recorded. This reading was then a measure of how far above the noise threshold the signal was. The resulting data are shown in Fig. 14. There are many fewer outliers, and the falloff is significantly smoother with distance.

Using the inline attenuator provides the advantages of power measurement: a clear comparison between different data points in units which are well-understood, while neatly



(a) Attenuator data



(b) Read rate data

Fig. 14. First environment measured with two different metrics

incorporating the tag's performance characteristics implicitly in the measurement. It also shows the expected falloff with distance which the read rate measurements lacked. It seems likely, therefore, that this measurement is a more informative indicator of read likelihood than read rates. Measuring the incident power alone on the tag is an incomplete measure of read quality, since there are many more variables to do with how the power is handled by the tag. The use of an inline attenuator in this manner should be investigated further in future experiments.

VII. Conclusions

This paper has shown two methods for measuring the performance of RFID systems in two different environments. The experiments set out to investigate the differences seen between two environments, and they led to refinement of the technique, specifically the development of a better metric. Measuring read power with the variable attenuator produced a significantly more predictable response than read rates. The results are promising, but indicate that further refinement of the data gathering method will be necessary to fully identify the sources of error. The next stage of this work will be to confirm the performance effects of the tag array as compared with the single tag. A more efficient method would also allow additional data to be recorded to derive better error data within the confines of the testing space. The further goal of the research is to draw conclusions about variations in the environment by conducting a planned collection of these experiments.

These experiments show that a wide range of performance can be found in a batch of tags, even one which is thought to have been selected for performance. They also show that measuring tag performance by read rate does not give results which are nearly as predictable as those measured by attenuation.

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