Assessing and Optimizing the Range of UHF RFID to Enable Real-World Pervasive Computing Applications

Steve Hodges, Alan Thorne[1], Hugo Mallinson[1], and Christian Floerkemeier[2]

Microsoft Research, 7 JJ Thomson Avenue,
Cambridge, CB3 0FB, UK
shodges@microsoft.com
[1] Cambridge Auto-ID Lab, Institute for Manufacturing, University of Cambridge
Mill Lane, Cambridge CB2 1RX, UK
ajt@eng.cam.ac.uk, hfm21@eng.cam.ac.uk
[2] ETH Zurich, Institute for Pervasive Computing
CH-8092 Zurich, Switzerland
floerkem@inf.ethz.ch

Abstract. Radio frequency identification (RFID) may be used to automatically detect, locate and/or identify objects, making it an ideal candidate for many pervasive computing applications. As RFID technology improves in terms of cost and performance, it is increasingly being explored in a variety of applications, ranging from eldercare through to the smart supply chain. However, while passive UHF RFID has many benefits over other RFID variants, reliable operation as the tag moves in the environment is inherently difficult to predict and can represent a significant challenge. In this paper, we present a novel and practical experimental method called attenuation-thresholding which may be used to characterize the operating range of such RFID systems. The results presented demonstrate the advantages of our method over the conventional read-rate approach. We also demonstrate a novel approach to collecting the measurements in range characterization experiments using robotic automation. Finally, we show how the application of attenuation-thresholding in combination with robotic automation can be used to optimize tag placement on an object. In addition to the clear relevance of this work to the many RFID-based pervasive computing applications reported in the literature and currently under development, it also has broad applicability in other RFID application domains. We conclude with a number of ideas for future extensions to this work.

1 Introduction

Radio-frequency identification (RFID) provides a relatively simple and cheap way to associate an electronic identity with a physical object. An RFID tag is attached to the object to be identified, and an associated RFID reader can then detect the presence of that object and determine its identity. This ability to augment objects (and even people) in a relatively light-weight manner and then use RFID readers in the operating environment to detect, identify and to some extent locate them, means that RFID technology is increasingly used in a number of pervasive computing application scenarios.

A. LaMarca et al. (Eds.): Pervasive 2007, LNCS 4480, pp. 280 – 297, 2007.

One of the most significant applications for RFID is supply chain automation through the replacement of barcode technology. The potential benefits of RFID tagging individual items and logistical units (boxes and pallets) in the consumer goods supply chain are huge [10], because the identity, location and authenticity of those items can be much more easily monitored [14, 30]. In turn, this creates the potential for increased efficiencies and cost savings [6, 19]. Whilst supply chain automation may be the largest single application for RFID, a huge number of other pervasive computing applications are made possible through the technology; examples include smart shelves, desktops and medicine cabinets [31, 8, 32], "Reminder Services" [4] and location monitoring of elders [25].

While passive RFID technology has many benefits over other technologies that might be used to detect, locate and/or identify objects [12, 15], reliability of operation as the tag moves in the environment is inherently difficult to predict and can represent a significant challenge. Although there are techniques for predicting the range of an RFID system which would in theory help designers to build systems with predictable operating performance, many of these are limited in practice. Instead, a typical UHF RFID system is designed very conservatively so that during use the tag will always be close enough to the RFID reader to ensure consistent operation.

In this paper, we present a novel and practical experimental method called attenuation-thresholding which may be used to characterize the operating range of UHF RFID systems. The results presented demonstrate the advantages of our method over the conventional read-rate approach. We also demonstrate a novel approach for the automation of measurements in range characterization. Finally, we show how the application of attenuation-thresholding in combination with robotic automation can be used to optimize tag placement on an object. In addition to the clear relevance of this work to the many RFID-based pervasive computing applications reported in the literature and currently under development, it also has broad applicability in other RFID application domains.

2 The Difficulties of Deploying UHF RFID Systems

In this paper we define the 'range' of an RFID system as being the volume of space in front of an RFID reader antenna in which an RFID tag can be reliably detected and identified. We do not want to formally define 'reliable', but we understand it to mean that a typical pervasive computing application will operate as envisaged by the designer whenever the tag(s) in the system are within 'range of the RFID reader'. More specifically, we actually refer to the range of the reader *antenna* – the antenna may be built into the same enclosure as the reader electronics, but with the UHF systems under consideration here, is often a separate unit connected to the reader with a cable.

The difficulties associated with determining the range of an RFID system stem from the complex nature of the RF field generated by the reader antenna. This field must power the RFID tag in order for the system to operate, and this is only possible if it is sufficiently powerful at a given location and if enough of the power available is transferred to the tag. Once the tag is powered, it must then transmit a signal back to the

RFID reader. It has been demonstrated that the limiting factor in this two-step process is typically delivering power to the tag [26], i.e. if the tag can be powered then the return path will be largely error-free. So modeling or measuring the strength of the RF field generated by an RFID reader is in essence the key to understanding its range.

At the simplest level, the strength of an RF field drops off as you move away from the antenna that is generating it according to the Friis Transmission Equation:

$$\frac{P_{tag}}{P_{reader}} = G_{tag} G_{reader} \left(\frac{\lambda}{4\pi R}\right)^2 \tag{1}$$

This says that the ratio of power received by the tag antenna (P_{tag}) to power input to the reader antenna (P_{reader}) is proportional to the gain of both the tag and reader antennas, (G_{tag} and G_{reader} respectively) and to the square of the wavelength (λ), and inversely proportional to the square of the distance between reader and tag (R). If you double the distance between reader and tag, the power available becomes one quarter of its previous level. However, the above equation applies only under ideal conditions. Whilst these ideal conditions can be artificially created in a purpose-built anechoic chamber[1], in reality a number of factors combine to change the actual field strength in a complex, non-intuitive, and hard to predict manner. These factors are:

Absorption: Any material between tag and reader will reduce the power available to the tag; the amount of degradation depends on the amount and nature of that material.

Multipath fading: Even if there is line-of-sight between reader antenna and tag, so-called fading effects can sometimes decrease, and sometimes increase, the read range. Fading is caused by interference between two or more versions of the transmitted signal, which travel along multiple (different) paths and combine at the receiver to result in a signal with widely varying strength. A localized area of particularly low signal strength within a region of generally higher strength is called a *null*; and in this paper we refer to the opposite condition as an *outlier*.

Polarization losses: The ability to power a tag is further significantly reduced by polarization losses, which occur when the RF energy from the reader is not polarized in the optimal orientation for the tag.

Impedance mismatch: Similarly, any impedance mismatch at the tag antenna will reduce the power available. Typically tags are designed to be impedance matched when operating in free space, and the proximity of the object to be tagged (no matter what it is made from) will have a de-tuning effect. Different materials will exhibit different effects.

As will be appreciated, the nature of the object to be tagged can have a dramatic effect on the range of a UHF RFID system – not only when that object comes between the tag and the reader, but also when the tag is in line-of-sight of the reader antenna, due to antenna de-tuning. Similarly, the orientation of the tag may change its ability to pick up RF energy at a certain location. However, the most insidious effect is multipath fading, where other objects in the environment, possibly items many metres away from both the tag and the reader, cause reflected signals that conspire to create

[1] This is a special isolated environment, typically the size of a small room, which is designed to be free from sources of interference in order to simplify the analysis of RF devices.

nulls and outliers, resulting in very unexpected results. This is particularly relevant for pervasive computing applications, where the environment is often uncontrolled.

It is possible to extend the Friis Transmission Equation to account for the additional factors listed above, and this approach is sometimes used to address specific issues (such as the de-tuning effects of the object to be tagged). However, it is often impractical to do this due to the complexity of the resulting model, the complexity of the data needed for the calculation, and the complexity of the calculation itself.

The simplest approach to deploying a reliable RFID system is to be conservative in the system design. However, it is nearly always desirable to maximize operating range because that usually leads to a less constrained user experience. This is especially true when using the more sophisticated tags that are being developed for some pervasive computing applications (such as [29]), due to the increased tag power consumption which acts to reduce range. Unfortunately, not many tools to accurately characterize or improve the range of an RFID system are available. Typically, the system designer will simply try out a specific configuration, and if it appears to work reliably, tweak it for optimal performance. A better approach to understanding and optimizing the range of RFID systems would be very valuable.

3 Previous Work Related to Assessing RFID Range

3.1 Building More Sophisticated Models

The obvious way to improve on the basic model presented in the previous section (Equation 1) is to analyze one or more additional factors from first principles and extend the model appropriately. One example is the use of a technique known as radar cross section (RCS) analysis to examine the performance of the RFID tag antenna [18, 24]. An RCS model can not only model the ability of a particular antenna design to communicate back to the reader, but may also account for impedance matching effects [24]. However, these factors are not typically dominant in determining the range of an RFID system.

Another common approach to extending the basic Friis Transmission Model is to run a number of experiments to characterize certain factors that influence RFID range and then incorporate additional terms in the model to reflect the effects that have been observed. For example, the reader and tag antennas will rarely have constant gain in all directions (as assumed in the Equation 1). Instead, they will frequently be *directional*, and the easiest way to characterize this is by measurement in an RF anechoic chamber. The resulting data (see Figure 2(b) later in the paper for an example) may be used to extend the Friis Equation. Since there are no external reflections or noise sources during the evaluation of the antenna, the readings can be assumed to be free from errors [17].

Another extension based on data collected in a series of experiments has been proposed in a recent study [13]. Here, the RF energy received by an RFID tag antenna in free space was measured, and this experiment was then repeated with the antenna attached to a number of different materials. For ease of testing, this was done using RF test equipment, rather than an RFID reader and tag. The authors not only present the measured data, which shows to what extent different materials reduce a tag's ability to receive RF energy, but they also demonstrate how their experimental results may be generalized to give different 'gain penalty' figures for those different materials. In this way, they suggest that the effect of tagging objects made from these materials may be predicted without the need for further measurements. However, it would appear that the experimental approach reported does not (sufficiently) model the de-tuning effect because the authors used a tunable impedance transformation network to reduce the effect of impedance mismatch. Also, the technique require that new experiments are run for additional materials (not previously analysed) or for complex objects. This cannot be done in the field at the time of RFID deployment without access to suitable RF test equipment.

More sophisticated models of RFID range are not reported in the literature, presumably due to the difficulties of generating and using them. Even the simple models presented above are largely in their infancy and have not been widely adopted.

3.2 Measuring the Strength of the RF Field

Since the delivery of power from the reader antenna to the tag is typically the limiting factor in an RFID system [26], the strength of the RF field itself is a useful metric for predicting range. This may be measured relatively simply using a field probe in conjunction with the appropriate RF test equipment. It also has the advantage that it becomes straightforward to introduce objects into the environment, such as the object that the tag is attached to, and to monitor the associated effect on field strength and therefore range. However, there are also a number of drawbacks. It is complicated to set up: the field probes may not have the same performance as the tags themselves; and ultimately only part of the RFID system is being evaluated.

A number of pieces of previous experimental work to measure RF field strength are reported in the literature. In [22] field probes are used to sense the RF energy available to an RFID tag when the tag and field probe are attached to a case of medical ampoules. To overcome inaccuracies due to the difference between the field probe antenna design and the RFID tag antenna, anechoic chamber antenna characterization is carried out. However, some difference between the performance of the probe and that of the tag will always remain. A different approach is used in [28] – here the field probe is essentially incorporated into a custom-built high performance RFID ‘tag’ which communicates to the RFID reader in the same way as a standard tag, but records RF field strength at the same time. This technique again introduces inaccuracies through the use of a custom antenna design which will differ from the chosen tag antenna.

3.3 Measuring the Extent of the Reader Field Using Read-Rate

The techniques reviewed so far are only of practical use for evaluating performance of *parts* of the RFID system. An ideal measure would take all factors affecting range in a real operating environment into account. There is actually one very simple way to assess RFID operating range, using a measure known as *read-rate* – the rate at which a reader can identify a tag [1, 16]. The essential idea is that the reader is put in a mode where it continually scans for the presence of an RFID tag. If a tag is detected, its identity is determined and recorded by the reader, whereupon the scan operation immediately repeats. Any error during the detection and identification stages will result in failure for that particular scan operation. When the tag is sufficiently powered, the number of errors will be (very close to) zero. However, as the tag-reader separation is increased, the chances of a communications error increase, and scan cycles will start to fail. Eventually the number of errors becomes so great that the reader will consistently fail to identify the tag.

The exact definition of 'read-rate' varies; typical approaches are to measure the number of successful reads per second or the ratio of successful cycles to the total number of cycles. The latter is more formally defined by:

$$r = N_r / N \tag{2}$$

where N represents the number of cycles, N_r is the number of successful cycles, and r is the read-rate (a dimensionless scalar between the values of 0 and 1) [16].

The advantage of read-rate is that it is very easy to measure – it is natively supported by (nearly) all RFID readers[2]. As a result, read-rate is by far the most widespread method used in practice in the authors' experience, across a wide variety of different application areas. It may also be used with tagged objects, and hence provides a straightforward way to incorporate any effects introduced by the object, which may of course be very significant. Indeed, [16] concludes that read-rate is a useful metric for determining reader-to-tag distance. However, as we show later in this paper, read-rate does not always correlate with distance between the reader and the tag as might be expected, and can therefore sometimes be quite misleading.

4 Evaluating Existing Approaches to RFID Range Characterization

4.1 Basic Theoretical Modeling for RFID Range Characterization

As a baseline for the experiments which follow in this paper, we used the Friis Transmission Equation in conjunction with a model of the reader antenna based on its measured radiation pattern to calculate the strength of the field generated by the reader. By making an assumption about the level of power required to operate a tag in the field, it is possible to predict the extent of the operating range across a simulated 3D space. Figure 4 (which occurs later in the paper to facilitate comparison with other figures) depicts this simulated data, based on the radiation pattern of a Cushcraft S9028PC antenna (see Figure 2 and [7]) and a fixed operating frequency of 915MHz.[3] Note the position of the reader antenna, also shown in the plot.

4.2 Experiment to Characterize RFID Range Using Read-Rate

As described in Section 3.3, read-rate has been used as an indicator of field-strength and/or range of an RFID system. However, we have not seen a systematic measurement of read-rate across the entire operating space of a UHF RFID system, which would result in a plot similar to the one in Figure 4. Perhaps one reason for this is simply the scale of such an experiment – previous experiments which have characterized RFID

---

[2] Generating read-rate data is very straightforward with all UHF readers that the authors have experience with.

[3] In practice the RFID reader will actually frequency-hop across a number of channels in the 902-928MHz band; we simplified calculations by approximating to the centre frequency.

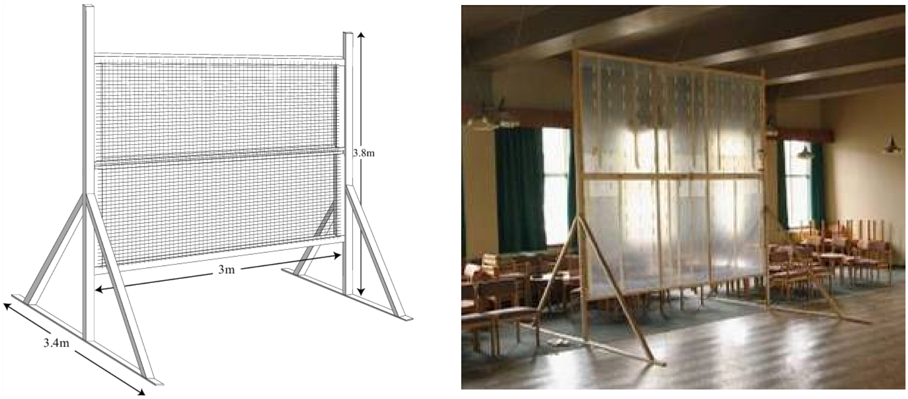


Fig. 1. The frame which supported the grid of tags was constructed of wood, with plastic overlaid for rigidity, and a sheet of thin plastic to which the tags were attached. The wooden chairs behind the frame in the photo were assumed to have negligible effect on RFID operation.

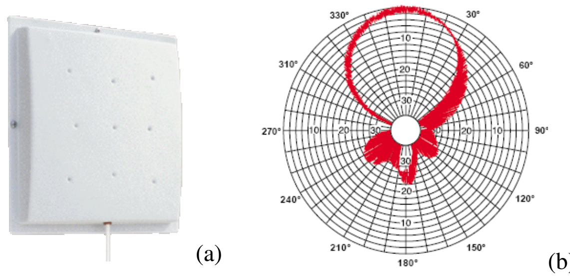
read fields [1, 9, 13, 16] have tested one tag position at a time. In particular, [1] used a grid marked out on the floor at set intervals, and a height-adjustable stand to which the tag was attached. The stand is manually placed at a certain location on the grid, a reading is taken; the stand is then moved and the next reading is taken. This has to be repeated for all of the grid locations and for all the tag heights under consideration, and is therefore considerably time-consuming. To minimize effects that may be introduced by the presence of a human body, it is important that the area under test is vacated by the operator(s) for each test, further increasing the testing time.

In the experiment reported here, read-rate was recorded for every point on a 20cm grid throughout a 6m x 3m x 3m volume in front of the reader antenna, for a total of 7,932 points. The measurements were carried out in a large, open room on the top floor of a two-storey building of steel-reinforced concrete construction. In order to reduce the time required to characterize the entire field, a 14x14 array of tags which could be tested in one operation was used. This array was supported by a 3m x 3m wooden frame with semi-rigid plastic netting attached to it to provide stability and with thin plastic sheeting stretched over the front to form a smooth surface for attaching the tags. The frame is depicted in Figure 1. No metal was used in its construction to minimize any effect of the frame on the RF field. All tags were at least 10cm from any of the wood in the frame, to minimize adverse de-tuning effects the proximity of wood might have on them.

An ALR-9750 915MHz RFID reader and a circularly polarized antenna supplied by Alien Technology were used. This reader runs the EPC class 1, generation 1 air interface protocol [2]. The circularly-polarized antenna, which is used for transmission and reception, results in consistent performance independent of the orientation of the tag (with respect to the reader antenna) in the plane parallel to the reader antenna, and so is a popular choice for many application scenarios[4]. Although an Alien part number or

[4] Despite the flexibility afforded by the circularly polarized antenna, all the data presented in this report was collected with the tag in a consistent orientation, namely vertical.

Fig. 2. Cushcraft S9028PC circularly polarized antenna. (a) photo and (b) H-plane radiation pattern. This antenna has a +7.5dBic gain, a VSWR of 1.5:1 and a -3dB cut-off at 65° for both H-plane and E-plane.



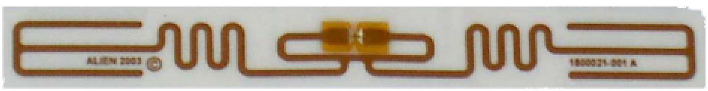


Fig. 3. Alien ALL-9340 ‘squiggle’ tag

datasheet was not available for the antenna, it believed to be very similar to the Cushcraft S9028PC antenna [7] depicted in Figure 2. The tags were Alien ALL-9340, 98.2 x 12.3 mm ‘squiggle’ tags, using their Omega revision silicon (Figure 3). Since the experiments were carried out in Europe before the availability of UHF RFID readers operating in the 868MHz band, a 915MHz test license was obtained.

The results of this extensive experiment are shown in Figure 5.

4.3 Discussion

The two approaches to characterizing the range of an RFID system presented in this section give quite different results. The Friis Transmission model leads to a well-defined prediction of read range – the sort of envelope that is often assumed in the literature. Of course, effects such as multipath fading, impedance mismatching and polarization changes are not taken into consideration in the model. On the other hand, the read-rate data naturally incorporates all these various factors, because it is collected from an operational RFID system. In particular, nulls and outliers are clearly present, presumably due to constructive and destructive interference from reflections; these are accentuated by the non-linear nature of read-rate data [26]. Whilst this data must be an accurate indication of which tags could and could not be read at different locations in the environment during the course of the experiment, it is not a realistic indicator of the extent of the operating range. Experience with real RFID deployments shows that outliers such as those shown in Fig. 5 are hard to replicate reliably and can in no way be predicted or relied upon. Similarly, whilst there may be nulls close to the reader antenna, small relative movements between the tag and the reader antenna (as would be expected in most real-world applications) will likely eliminate these.

We conclude that neither of the approaches outlined here are good candidates for predicting RFID range, for quite different reasons. It is possible that an approach based on field probes would be more successful, but this would have disadvantages such as the need for specialized test equipment and/or instrumented tags. The next section introduces a new technique developed to overcome weakness of read-rate testing but without requiring expensive test equipment or instrumented tags.

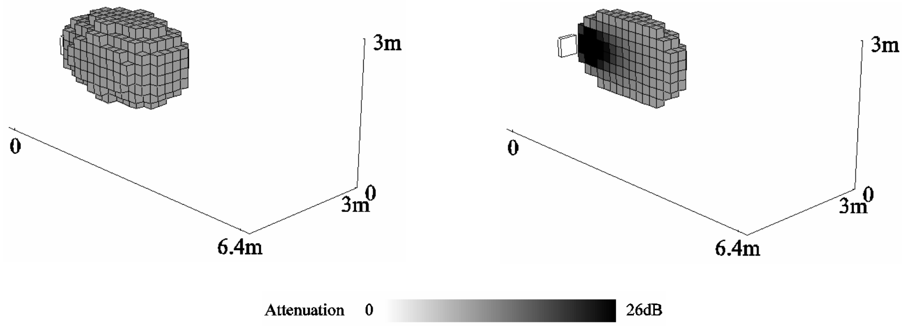


Fig. 4. The RF field strength as predicted using the Friis Transmission Equation. The cut-away view clearly shows the field strength variation and depicts the reader antenna location.

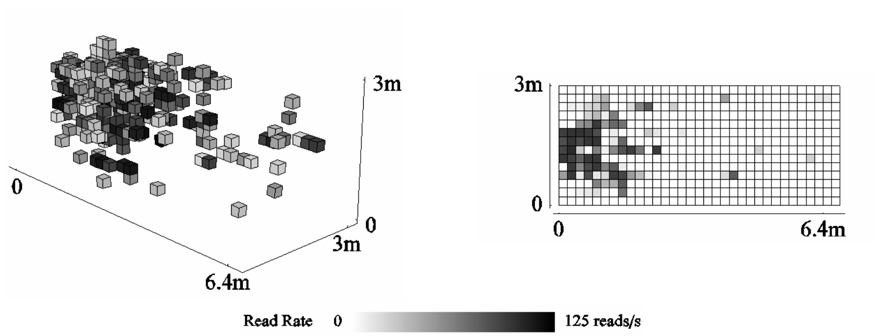


Fig. 5. Read-rate data, 3D view and a 2D view of a horizontal slice through the data

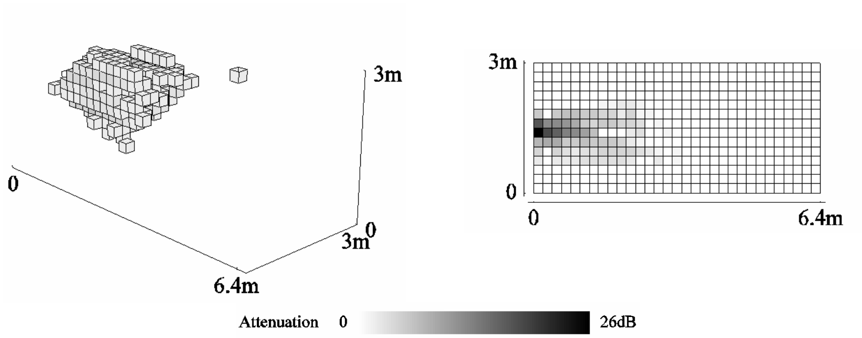


Fig. 6. Attenuator-thresholding gives a much more realistic indication of operating range

5 Introducing Attenuation-Thresholding: A New Approach to RFID Range Measurement

5.1 Experimental Setup for Attenuator-Thresholding

We have developed a new approach for measuring the performance of an RFID system, which we believe is nearly as easy to use as the read-rate metric, but is a much better indicator of RFID system range. We use a programmable attenuator to selectively degrade the signal that passes between a standard RFID reader and its antenna. By increasing the attenuation automatically (under computer control) until the tag read-rate drops below a chosen threshold, it is possible to determine and record the RF margin (i.e. how much power is available in excess of the minimum required to operate the tag) for each location tested. We call this technique *attenuation-thresholding*.

For the attenuation-thresholding experiments reported here, we used the same RFID equipment as outlined in Section 4.2, in conjunction with a Pasternack PE7011-6A programmable attenuator [23]. This was connected between the RFID reader's single antenna port and the reader antenna. It has a DC to 1GHz operating range, a maximum VSWR of 1.4:1, an insertion loss of 2dB and can be digitally controlled to insert up to 63dB in 1dB steps (±0.3dB). The power rating of the attenuator is 0.5W average, 50W peak, which is compatible with the EPC Class 1 Generation 1 specifications [2]. The total level of attenuation introduced is controlled via six separate stages which are connected in series inside the unit. There are six inputs to the device; applying 12V to an input enables the corresponding attenuation stage. A microcontroller-based custom interface was constructed to allow the attenuator to be controlled from a PC via a serial port. We used a threshold read-rate of zero for these experiments.

5.2 Results

We ran an antenna-thresholding experiment using the tag array of Section 4.2 in order to compare the technique directly with the read-rate analysis presented in the previous section. The results are shown in Figure 6. As can be seen, even though it intrinsically captures factors such as multipath fading and polarization losses, the data is much less noisy than for the read-rate testing.

5.3 Discussion

The comparison of the read-rate measurements with the attenuation-thresholding approach shows that the data captured with the latter technique is much less noisy, even though it intrinsically captures factors such as multipath fading and polarization losses. We believe that this is at least partly caused by the fact that attenuator introduces an additional loss of 2dB. This will simply remove some of the outliers due to the overall reduction in field strength. However, much more importantly, attenuation-thresholding much more effectively shows the reduction in power margin as the tag is moved away from the antenna. The read-rate approach is not suitable for determining the power distribution in the vicinity of the reader, since read-rate vs. power at the tag is a highly non-linear function [26]. The true power distribution inherently measured with attenuation-thresholding is essential for predicting the operating range under different conditions, e.g., in the presence of interference from other transmitters, or tag detuning. Attenuator-thresholding is thus an easy-to-use technique, which requires little additional hardware beyond a standard RFID system set-up and yet produces much more useful information about the operating range of an RFID system than read-rate analysis, which is commonly used today.

5.4 Limitations of Evaluating a Large Workspace

The experiments presented so far use an array of 196 tags to map out the size and shape of the usable workspace for an RFID system. However, there are some limitations to this approach and we have subsequently developed an experimental technique which completely automates RFID system range testing using robotic automation. An RFID tag is attached to the end-effector of a robot using a non-conductive mount (to reduce the influence of the robot itself on tag operation) and the robot is controlled so as to move that tag sequentially between each of the positions to be evaluated. At each position, a read-rate or attenuation-thresholding test may be performed. In this way, the entire range characterization may be carried out without any manual intervention no matter how many different test positions are required. By using the same tag at each location, there are no discrepancies due to variations between tags (which is likely the case with the array of tags used in Sections 4.2 and 5.1). Since the robot can move at speeds of over $1ms^{-1}$, the method is fast even though data is collected one point at a time. The programmed locations for the end-effector of the robot (and hence the tag under test) will be very accurate, typically within 1mm.

In order to evaluate this technique, we attached a tag to the end-effector of a Fanuc M6i industrial robot [11]. This is an anthropomorphic style robot arm with ±0.1mm end-effector positioning repeatability and 6kg lifting capacity, designed for general purpose factory automation tasks such as arc welding and loading/unloading parts. Under computer control, we instructed the robot controller to move to each test position in turn, running a read-rate test (in this case) at each location. A fixed 10dB attenuator was inserted inline between the reader and the reader antenna in order to artificially limit the range of the RFID system without altering the shape of the field. This technique, which has been previously reported in the literature, limits the extent of the field to within the reachable workspace of the M6i robot. Figure 7 shows a dataset gathered using this technique.

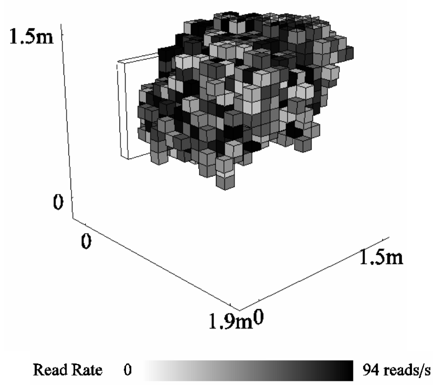


Fig. 7. Read-rate testing using robotic automation to move a tag sequentially between each test position. The reader antenna location is shown at the back of the plot.

Robotic range testing overcomes another major limitation common to much RFID system analysis, namely the labour-intensive and time-consuming nature of testing. The RFID evaluation system based on the use of robotic automation presented here alleviates these issues, and therefore provides a versatile platform for extensive characterization of RFID operation in new ways that have previously been impractical. In the next section, we demonstrate the use of attenuation-thresholding in combination with robotic automation to find the best place to put a tag on an object.

6 Using Robotic Attenuation-Thresholding to Determine Where to Tag an Object

6.1 The Importance of the Object to Be Tagged

In the analyses presented so far, the range of an RFID system has been characterized for a tag in free space i.e. not affixed to an object. Of course, in real applications the tag will be attached to an object of some description – and the introduction of such an object will in many cases have a significant impact on the performance of the RFID system. Whilst the theoretical model of the reader field strength cannot be trivially extended to incorporate all the effects the object to be tagged may introduce, the experimental techniques reported in this paper do support this obvious enhancement.

However, before assessing the usable workspace over which a tagged object may be reliably detected, it is important to choose the best location for the tag on that object. If the object is of non-uniform composition, the location of the tag on the object may be significant – some locations would lead to much more degradation in performance than others. Due to the complex nature of the interaction between the tag and the object, predicting the best location is not straightforward. In this section we present a new experimental technique to methodically determine the optimal tag position.

6.2 Assessing Different Tag Locations on an Object Using Tag Mapping

In order to support the choice of tag location, we have extended the robotic automation technique described in Section 5.4 to allow the position of the tag on the object to be varied automatically. In this case, the tag is not actually stuck down to the object as would normally be the case, but is instead held against the surface of the object using two thin, flexible plastic fingers, see Figure 8 for details. Note that this tag positioning arrangement has no measurable effect on the RFID system performance. The tag is held flat against the face of the product, even along curved faces or around edges. We call this technique *tag mapping*.

To demonstrate the ability to measure the performance of different tag positions on an object, we applied this technique to a case containing six bottles of wine, which was purchased from a local supermarket. This object was chosen due to interest in tag mapping from colleagues working on pervasive computing supply chain applications.

Fig. 8. The custom tag holder allows the RFID tag to be pressed against an object as if it were actually stuck down. Two compliant 'fingers' are made from loops of 9x.75mm polyethylene (to the left and right of the tag) and are attached to the robot end-effector using a fairly RF-transparent material. An RFID reader antenna can be seen in the background.

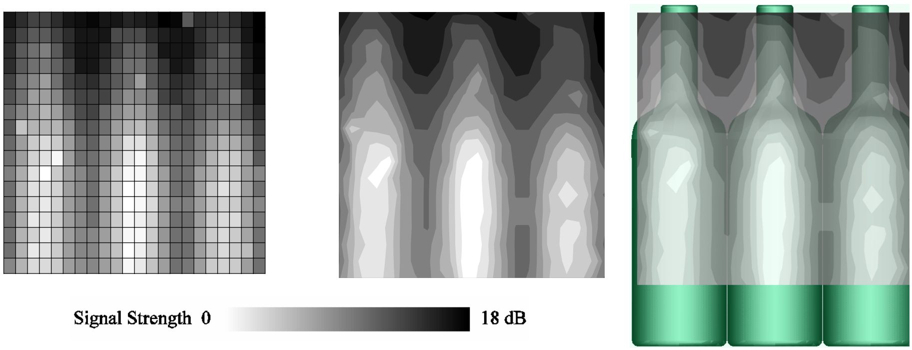


Fig. 9. The results of testing one face of the case of wine. The raw 'pixel' data is shown (left) along with averaged 'contour' data (centre) which more clearly shows how the shape of the wine bottles effects the performance of the tag. The same contour plot is superimposed on a 3D model of the wine bottles to demonstrate the close correlation.

The detrimental effect of proximity to water on the operation of an RFID tag is well established. We would therefore expect the tag to perform badly when placed towards the bottom of the case, where it is in closest proximity to the wine bottles, and to perform much better right at the top of the case, where the bottles narrow and there is much more free space inside the case. The generated tag map should reflect this.

The M6i robot was used, but in this experiment the tag was fixed in space and the case of wine was moved relative to it in order to simulate the different possible tag positions. A total of 374 candidate locations were evaluated across a single face of the case. The tag orientation was fixed throughout the experiments.

6.3 Tag Mapping Results

The tag map produced from the case of wine is shown in Figure 9. The raw 'pixel' data shown on the left represents the degradation introduced by the presence of the object when the tag is placed so that its centre is positioned at each pixel in turn.

6.4 Comparing the Performance of Different Tag Locations as an Object Moves Away from the RFID Reader Antenna

The final experimental results presented here show how robotic attenuation-thresholding can be used to determine any changes in the tag placement map as the

Fig. 10. Fanuc M6i and M16i/T robots (left and right respectively). The M16i/T used in this work had a 12m gantry that allowed 11.2m of movement. The M6i was fixed at a height of 1m from the ground.

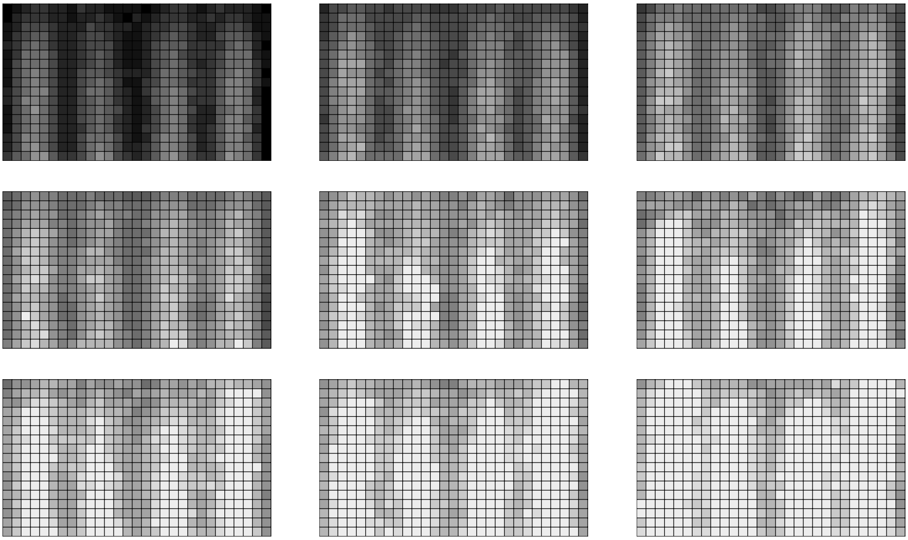
tagged object is moved relative to the RFID reader antenna. For this type of experiment, a second robot is required – we used a Fanuc M16/iT robot arm mounted on a gantry, allowing robot arm itself to move through 11.2m (along the length of the gantry). Instead of moving the object to different locations in front of the reader antenna, we actually attached the reader antenna to the M16 end-effector. The M6i and M16i/T robots are shown in Figure 10.

Modified control software was used to synchronize the movement of the two robots so that for each candidate object location, a separate tag placement map was measured. For this experiment, a different (although similar) object was tested, namely a case of twelve 50cl bottles of Vittel spring water. Figure 11 shows an external view of the case, as mounted on the robot end-effector, and a photograph of the contents of the case (as viewed from above).

6.5 Results of Tag Map Comparison Experiments

Two particular scenarios are reported here. The first of these investigates how the tag placement map varies as the tagged object moves away from the reader antenna, by

Fig. 11. A photo of one of the 50cl Vittel bottles (left), the inside of the box of Vittel under test, and robot end-effector mounting details for the box



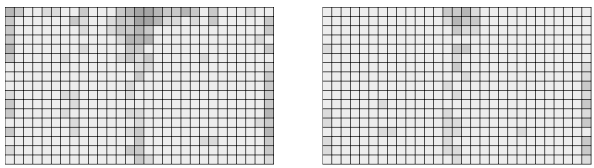


Fig. 12. Tag maps for the case of Vittel spring water for a number of different distances from the reader antenna. Key as Figure 13.

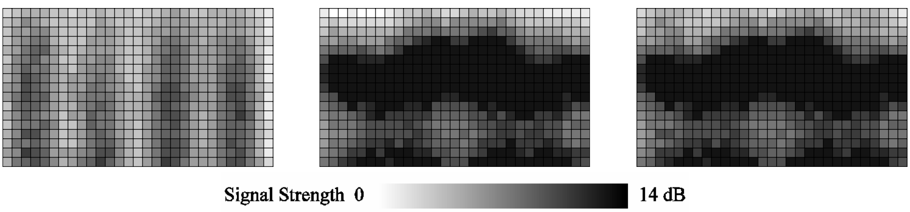


Fig. 13. The tag maps for the case of Vittel spring water when the tagged surface is facing towards the reader (left) and away from the reader (centre). Also shown is the 'worst-case' combination of these two tag maps (right), which demonstrates the minimum performance that could be expected if either case orientation is possible (and not known in advance).

recording a tag map at a series of distances from the reader antenna, each 100mm more than the previous. The results of this test are shown in Figure 12.

In many pervasive computing applications it is not possible to constrain a tagged object so that the tag is always facing the RFID reader antenna. The second test investigates what happens if the tagged object is rotated through 180° so that the tagged surface is facing *away* from the reader antenna, usually the worst-case scenario in terms of RFID operating range. As Figure 13 shows, the map of good and bad tag locations is very different when the tag is on the reverse side of the case. If the orientation of the case with respect to the reader is not known in advance, i.e. if the tag could be facing the reader or on the opposite side, then the map depicted on the right of Figure 13, which takes the worst-case elements of the two different conditions, should be used.

7 Conclusions and Future Work

We have presented two novel and practical experimental methods, namely attenuation-thresholding and the use of robotic automation. These may be used to assess and optimize the operating range of UHF RFID systems much more effectively than conventional approaches. Although we used custom-built hardware, we observe that the ability to programmatically control output power is increasingly being incorporated in off-the-shelf RFID readers. As a result, in many instances it is now possible to implement attenuation-thresholding using a simple script to control a reader remotely. We strongly encourage those deploying RFID in real-world applications to use this approach instead of using read-rate. The use of a robot to automate testing means that the effort required to measure RFID operating range is significantly reduced and the precision of the data collected is increased. Whilst the robot-assisted approach will be inaccessible to many researchers deploying RFID-based pervasive computing systems, we hope in time to characterize the performance of a range of different types of object, creating a kind of reference database which would be of direct relevance to practitioners. It may also be possible to create a third-party service of some kind (such as a test centre) to evaluate specific scenarios.

Additionally, our work on finding the best place to put a tag on a given object can deliver a significant improvement in RFID performance by systematically evaluating every possible tag position. This technique could be readily extended to compare the performance of different RFID readers or different tags, and in particular of different tag antenna designs. Variation in tag orientation could also be considered.

The limitations to our work are highlighted in the discussion section. While we can accurately assess the operating range of an RFID system in a given environment, it will not always be appropriate to assume the same operating range will apply in a different environment, due to the small-scale fading effects observed in the UHF frequency band. However, the data captured across different environments might help to parameterize statistical fading models, such as Rayleigh and Rician fading [27]. In this way, it would be possible to build extensions to the Friis Transmission Equation in order to model certain common scenarios faced during the design of RFID-based pervasive computing applications. We are currently actively working on this. We are also interested in the possibility of extending work in the literature (such as [20]) to build more accurate location systems built on RFID with attenuation-thresholding.

References

1. Alien Technology, "RFID training course materials," 2003.
2. Auto-ID Center, "860MHz-930MHz Class 1 Radio Frequency (RF) Identification tag radio frequency & logical communication interface specification", EPCGlobal Inc, http://www.epcglobalinc.com/standards_technology/Secure/v1.0/UHF-class1.pdf, 2002.

3. T. Balch, A. Feldman, and W. P. Wilson, “Assessment of an RFID system for animal tracking,” Tech. Rep. GIT-CC-04-10, Georgia Institute of Technology, 2004.
4. G. Borriello, W. Brunette, M. Hall, C. Hartung and C. Tangney, Reminding about Tagged Objects using Passive RFIDs, Ubicomp 2004.
5. L. V. Blake, Radar Range-Performance Analysis. Lexington Books, 1980.
6. G. Chappell, D. Durdan, G. Gilbert, L. Ginsberg, J. Smith and J. Tobolski, Auto-ID on Delivery: The Value of Auto-ID Technology in the Retail Supply Chain, Auto-ID Center whitepaper, ACN-AUTOID-BC-004, 2002.
7. Cushcraft, “S9028PC12NF product datasheet,” Cushcraft, Inc, http://www.cushcraft.com/comm/support/pdf/S9028PC12NF.pdf
8. C. Decker, U. Kubach and M. Beigl, Revealing the Retail Black Box by Interaction Sensing, Proceedings of the ICDCS 2003, Providence, Rhode Island, 2003.
9. D. M. Dobkin and S. W. Weigand, “Environmental Effects on RFID Tag Antennas”, Microwave Symposium Digest, 2005 IEEE MTT-S International Microwave Symposium, 2005.
10. The Economist, “The best thing since the barcode”, February 2003.
11. Fanuc Robotics, Fanuc M6 and M16 series product overview, http://www.fanuc.co.jp/ja/product/catalog/pdf/m6ib-je03.pdf
12. K. Finkenzeller, RFID Handbook: Fundamentals and Applications in Contactless Smart Cards and Identification. John Wiley & Sons, May 2003.
13. J. D. Griffin, G. D. Durgin, A. Haldi and B. Kippelen, “RF Tag Antenna Performance on Various Materials Using Radio Link Budgets”, IEEE Antennas and Wireless Propagation Letters, Volume 5, 2006.
14. J. Hightower and G. Borriello, Location systems for ubiquitous computing, IEEE Computer volume 34, 2001.
15. S. Hodges and D. McFarlane, “RFID: The concept and the impact”, pp 55-75, “The Security Economy”, Organisation for Economic Cooperation and Development, 2004. ISBN 92-64-10772-X. Available at http://www1.oecd.org/publications/e-book/0304031E.PDF
16. B. Jiang, K. P. Fishkin, S. Roy and M. Philipose. “Unobtrusive Long-Range Detection of Passive RFID Tag Motion”, IEEE Transactions on Instrumentation and Measurement, Vol. 55, No. 1, Ferurary 2006
17. J. D. Kraus, Antennas. McGraw-Hill Education, second edition, May 1988.
18. H. Kwon and B. Lee, “Evaluation of RFID Tag Antenna Performance Using Radar Cross Sections”, The European Conference on Wireless Technology, pp 491-493, 2005.
19. H. Lee, B. Peleg, P. Rajwat, S. Sarma and B. Subirana, Assessing the Value of RFID Technology and the EPC Standard for Manufacturers, EPCGlobal Whitepaper, 2005.
20. X. Liu, M. Corner and P. Shenoy, Ferret: RFID Localization for Pervasive Multimedia, Proceedings of the 8th International Conference on Ubiquitous Computing, September 2006.
21. H. Mallinson, S. Hodges and A. Thorne. Determining a Better Metric for RFID Performance in Environments with Varying Noise Levels, 12th IEEE International Conference on Methods and Models in Automation and Robotics, 2006.
22. J. Mitsugi and H. Hada, “Experimental Study on UHF passive RFID Readability Degradation”, Proceedings of the International Symposium on Applicatoins and the Internet Workshops, 2005
23. P7011-6A programmable attenuator DC to 1,000MHz datasheet, Pasternack Enterprises LLC, http://www.pasternack.com/Pdf/PE7011-6A.pdf

24. K. Penttilä, M. Keskilammi, L. Sydänheimo and M. Kivikoski, “Radar cross-section analysis for passive RFID systems”, IEE Proceedings of Microwave Antenna and Propagation, Volume 153, Number 1, February 2006.
25. M. Philipose, K.P. Fishkin, M. Perkowitz, D.J. Patterson, D. Fox, H. Kautz, D. Hahnel, “Inferring activities from interactions with objects” IEEE Pervasive Computing, Volume 3, Issue 4, Oct-Dec 2004 pp. 50 – 57.
26. K. M. Ramakrishnan and D. D. Deavours. “Performance Benchmarks for Passive UHF RFID Tags”, Proceedings of the 13th GI/ITG Conference on Measurement, Modeling, and Evaluation of Computer and Communication Systems, 2006, pp. 137-154.
27. T. S. Rappaport, “Wireless communications”, 2nd edition, Prentice Hall, 2002.
28. R. Redemske and R. Fletcher, “Design of UHF RFID Emulators with Applications to RFID Testing and Data Transport”, Proceedings of 4th IEEE Conference on Automatic Identification Technologies, October 2005.
29. J. R. Smith, A. Sample, P. Powledge, A. Mamishev, S. Roy. “A wirelessly powered platform for sensing and computation” Proceedings of Ubicomp 2006: 8th International Conference on Ubiquitous Computing. Orange Country, CA, USA, September 17-21 2006, pp. 495-506.
30. T. Staake, F. Thiesse and E. Fleisch, Extending the EPC network: the potential of RFID in anti-counterfeiting, SAC '05: Proceedings of the 2005 ACM Symposium on Applied Computing, pp 1607-1612, 2005.
31. D. Wan, Magic Medicine Cabinet: A Situated Portal for Consumer Healthcare, Proceedings of the International Symposium on Handheld and Ubiquitous Computing, Karlsruhe, Germany, 1999.
32. R. Want, K.O. Fishkin, A. Gujar and B.L. Harrison, Bridging Physical and Virtual Worlds with Electronic Tags, Proc. of ACM SIGCHI, pp 370-377, 1999.