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Institute for Computing Systems Architecture

A Case for RFID-based Mobile Sensor Data Gathering in Indoor Environments

by

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Abstract : We propose the use of RFID in sensing applications enabled by passive or semi-passive tags and mobile devices equipped with readers. We experimentally investigate the feasibility of such RFID-based mobile sensor data gathering applications, focusing on UHF RFID devices and indoor scenarios. We examine the impact of various factors, including reader mobility, antenna types and orientation, multiple closely located tags and the presence of people on read range and other key related metrics. Our measurement results suggest the feasibility of using RFID for such applications and also provide useful insights for further improving read performance.

Keywords : Mobile sensor data gathering, Smart phones, RFID-enabled mobile devices, RFID sensors.

1 Introduction

Radio Frequency IDentification (RFID) [1, 2] is a wireless communication technology intended as an alternative to bar-codes for automatic identification of objects. Although not as cheap as bar-codes, RFID tags offer several powerful capabilities that make them more flexible and widely applicable. Unlike bar-codes, RFID tags provide a larger set of unique IDs and allow fast identification of multiple co-located tagged objects from a distance without requiring line of sight. Moreover, RFID tags can have embedded computing capabilities, store much more additional data beyond the ID information and can also be interfaced with environmental sensors and digital data sources. The lowering costs and increasing sophistication of RFID tags coupled with the emergence of standards (e.g., EPCglobal Class 1 Gen 2 standard [3] and the associated ISO 18000-6C) have led to significant and renewed interest in this technology with a plethora of applications in diverse domains, including supply chain, retail, transportation and healthcare for tracking, access control and wireless commerce.

We consider an important and emerging class of RFID applications — *the use of RFID in sensing applications* [4, 5]. Of particular interest in this context are passive and semi-passive tags equipped with sensing capabilities as they can potentially last a very long time while still being fairly cheap. Passive sensor tags like ordinary passive tags are powered by readers, so can sense only in the presence of a reader. Semi-passive tags like passive tags depend on power from reader for communication, but use a battery for continuous sensing. Several instances of integrating sensing capabilities into passive and semi-passive RFID tags exist, both commercially and as research prototypes. Examples on the commercial side include VarioSens temperature logger tag from KSW-Microtec [6] and temperature logger UHF semi-passive tag from CAEN RFID [7]. Notable research prototypes include bacterial sensor tags from Auburn University mentioned in [4] and WISP battery-less passive tags from Intel [8].

Leveraging the emerging trends toward mobile handheld devices equipped with compact, power-efficient and low cost RFID readers, we propose a mobile sensor data gathering paradigm based on RFID technology for low cost sensing in indoor environments (including offices, homes and hotspots). Our paradigm essentially involves gathering data from densely deployed static sensor tags using mobile devices carried by people (e.g., cell phones, handhelds, PDAs) that are equipped with RFID readers. Compared to other alternative approaches for indoor sensing applications, the proposed paradigm offers significant advantages in terms of cost and long-lived operation. The proposed paradigm, though similar to the data MULE approach [9, 10], allows for denser tag deployments in comparison. Our usage model also differs from other RFID-based sensing approaches such as in the WISP project [8].

We experimentally investigate the feasibility of RFID-based mobile sensor data gathering applications by focusing on UHF RFID devices and conducting a detailed characterization study in an indoor environment. We examine the impact of various factors, including reader mobility, antenna types and orientation, multiple closely located tags and the presence of people on read range and related key metrics. Our results show that read ranges around 1-2m are feasible at walking speeds with careful planning, thus suggesting the feasibility of the proposed class of applications. They also provide insights for optimizing read performance and enabling more ad-hoc deployments. Tag aggregation is proposed as an effective way to compensate for shorter read range and to deal with tag disorientation. We also find the presence of people has a beneficial impact on read performance with some antennas. Our work differs from the past experimental read characterization studies [11, 12, 13, 14] in that we consider mobile reader scenarios and look at reader-tag communication in the context of a specific class of applications, i.e., RFID-based mobile sensor data gathering applications.

The remainder of this paper is structured as follows. Next section describes our proposed paradigm of RFID-based mobile sensor data gathering. In Section 3, we carry out a detailed experimental characterization study of UHF read properties in indoor environments from the viewpoint of proposed class of applications. In Section 4, we discuss related UHF RFID read performance studies and conclude in Section 5.

2 Low Cost RFID Sensing

In this section, we describe the RFID-based mobile sensor data gathering paradigm proposed in this paper.

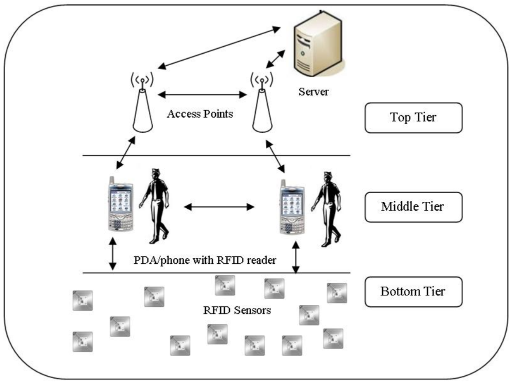

Figure 1: Three-tier architecture for RFID-based mobile sensor data gathering.

Sensor Data Gathering Alternatives

We begin by discussing various sensor data gathering alternatives for a generic sensing application that involves monitoring of some physical phenomena (e.g., temperature).

The simplest and the most expensive approach to sensor data gathering is to connect embedded computing devices with sensing capabilities using a wired network and powered from the grid. High cost associated with this approach prevents spatially dense sensing over a larger geographical area. A natural improvement to this approach for lowering the deployment cost is to move to a setting where sensor nodes are instead battery powered and communicate wirelessly. This is the approach adopted by the early wireless sensor network deployments based on motes in the late nineties [15]. The main challenge for this approach is increasing useful network lifetime given the limited node battery power and the need to relay sensed data over multiple wireless hops from the data sources to the sinks in the infrastructure. To overcome this challenge, a hybrid/heterogeneous architecture [16] has gained wider acceptance. In such an architecture, some grid-powered powerful wireless devices (e.g., Intel's Stargate platform), typically referred to as micro-servers, form a relay network between the many inexpensive battery-powered sensor devices (e.g., motes) and the wired infrastructure — sensor nodes forward the sensed data to the nearest node in the intermediate relay network using short-range wireless communication leading to power savings at the sensor nodes.

While the above hybrid approach is indeed better than the other two in terms of cost and long-lived operation, it can be further optimized by replacing the fixed micro-servers in the intermediate relay network with fewer mobile nodes as in the *data MULE* approach [9, 10] for applications that can tolerate higher latencies. In the data MULE approach, the mobile nodes (MULEs) pick up sensed data when they come in close proximity to the sensor nodes and buffer it until they can hand it off to the wired infrastructure or other such MULEs. The latency involved in communicating the sensed data to the infrastructure can be higher than the aforementioned hybrid approach and is dependent on the number of MULEs in the system and their mobility patterns. But on the positive side, the MULE approach by exploiting the mobile entities already present in the environment not only eliminates the need for deploying micro-servers but also can permit even shorter-range wireless communication by sensor nodes.

RFID-based Mobile Sensor Data Gathering

We propose a mobile sensor data gathering paradigm based on RFID technology for low cost sensing in *indoor* environments (including offices, homes and hotspots). Our paradigm essentially involves gathering data from densely deployed static sensor tags using mobile devices carried by people (e.g., cell phones, handhelds, PDAs) that are equipped with RFID readers. Figure 1 illustrates the three-tier architecture corresponding to our paradigm.

The *bottom tier* in the architecture interfaces with the physical world; it consists of passive or semi-passive sensor tags. Passive sensor tags like ordinary passive tags are powered by readers, so can sense only in the presence of a reader. Semi-passive sensor tags additionally have battery that allows continuous sensing but they still depend on power from reader for communication as with passive tags. As noted at the outset, the technology required for such sensor tags is already becoming available (see [7, 6, 17, 4, 8]). The most attractive aspect about these tags is that they are available at a fraction of the cost (or lower) compared to mote-class devices commonly used in wireless sensor networks, while still ensuring quite a long lifetime — passive tags have infinite lifetime in theory, whereas the battery life for semi-passive tags can be anywhere from 3 to 5 years for acceptable sampling intervals (see [7], for example). Moreover, they come with enough on-board storage capacity (tens of kilobytes) to store several thousand samples.

The *middle tier* in the architecture consists of mobile devices carried by people (e.g., cell phones, handhelds, PDAs) that are equipped with RFID readers. Note that HF-based mobile phone and handheld readers have been around for a few years (e.g., Nokia 5140 reader, Baracoda's IDBlue) supporting applications such as personal diagnostics [18]. But our focus here is on UHF readers interfaced to mobile devices for longer read ranges and higher rates for enabling diverse, larger-scale and opportunistic sensing applications. We expect such readers to be commercially available in near future with the emergence of compact, power efficient and low cost readers (e.g., readers based on Impinj Indy R1000 integrated RFID Transceiver chip [19]). Besides the reader, typical smart mobile phones and handhelds nowadays have several built-in wireless connectivity options (e.g., 3G, WiFi, Bluetooth) and large internal or expandable storage capacity in the order of several GB of flash memory. Also the usage model of these mobile devices is such that the battery is recharged by the user as needed. The aforementioned features together enabled the mobile devices equipped with UHF readers to be used for gathering sensor data when in proximity of sensor tags and store it temporarily if needed before transferring the data to an access point (AP) connected to a server in the wired infrastructure for further data analysis. APs together form the *top tier* in the architecture. In a real deployment, we expect the communication between the top two tiers to take place over WiFi as such infrastructure is already commonplace in many in-building scenarios, but in principle one could use any access technology providing adequate coverage and is supported by both APs and mobile devices (e.g., 3G). We also allow the possibility of mobile devices to exchange gathered sensor data with each other (over WiFi or Bluetooth, for example) as an optimization to expedite the transfer process. Finally, we assume that mobile devices *opportunistically* try to gather sensor data transparent to the user while making sure that user and application requirements (e.g., privacy, power consumption) are met as in [20]; in practice it would be necessary to provide appropriate user incentives to enable such opportunistic and transparent use.

We note that our paradigm is similar to the data MULE approach [9, 10] with the following two key differences: (i) unlike the data MULE approach, there is lesser emphasis on optimizing power consumption of sensing devices in our approach, especially when using passive sensor tags; (ii) in contrast to the data MULE approach, sensor deployment in our approach could be denser for enhanced robustness and additional redundancy to compensate for shorter read ranges. We also note that our usage model differs from that in other RFID-based sensing approaches. For instance, the WISP project [8] assumes a usage model in which passive sensor tags with ambient-power-scavenging (wisps) are attached to mobile objects (e.g., people) and long-range, grid-powered RFID readers distributed in the area to be observed continuously scan the area to sense activity. It is important to note that the proposed architecture is quite flexible in that it can be adapted to suit the application in hand. For example, the middle and bottom tiers can be coalesced together by attaching the sensor tag to the mobile device itself depending on the application, and even have mobile devices immediately upload sensed data (via cellular up-links, for example) in order to obtain a different cost-latency tradeoff.

To summarize, the proposed RFID-based approach offers a low cost alternative to sensing in indoor environments while also providing long-lived and flexible operation. Deployment costs are lowered because of two reasons: (i) no need for new infrastructure as a result of exploiting mobile devices existing in the environment; (ii) use of inexpensive sensor tags. Even operational costs would be lowered since the sensor tags need to be replaced very infrequently (every few years even with semi-passive sensor tags). We already noted the flexibility benefit above. Additionally, since the reader-tag communication is based on standard protocols independent of the type of sensors on the tags, the same deployment can be used across several different applications using different sensing modalities. The proposed approach can also lead to improved robustness when there are large number of participating mobile devices in the environment. On the downside, latency for transferring the data from the sensors to the wired infrastructure can be high and unpredictable; in the worst case, the collected sensor data may be incomplete if some tags do not happen to fall in the readable range of any mobile device in the environment.

Sample Applications

Broadly speaking, the proposed RFID-based mobile sensor data gathering approach can support indoor sensing applications that can tolerate higher latencies (from several hours to a day) and some degree of incompleteness and errors in the collected data. Such applications tend to monitor the aggregate state of the environment relatively infrequently (e.g., once a day) and are not concerned with the absolute accuracy and availability of individual sensor readings. Most building automation applications (e.g., HVAC control, lighting control, environmental monitoring) and "presence" monitoring applications (e.g., class attendance, room occupancy, postal mail alerting in large buildings) fall under this category. For instance, in a class attendance monitoring application, one is interested in monitoring the attendance levels of each class over an entire semester period in order to correlate with intensive project work periods in the semester and average performance levels. Using the proposed approach, one could tag all seats in every classroom so that seat occupancy can be sensed and the resulting data gathered via mobile phones carried by students themselves. In comparison, realizing this application using other approaches (e.g., manually attendance noting by the instructor, tagging each student) can be more disruptive or hurt peoples' productivity.

3 Experimental Characterization of UHF RFID Read Properties in Indoor Environments

3.1 Goals and Metrics

In this section, we experimentally study read characteristics of state-of-the-art UHF RFID hardware in order to assess the feasibility of the RFID-based mobile sensor data gathering paradigm introduced in the previous section. We evaluate the impact of a wide range of factors that could potentially affect read performance, including: tag and antenna types, relative reader-tag orientation, presence of people, impact of multiple closely spaced tags and reader mobility. We use the following set of metrics to quantify read performance in our experiments:

- *Read range*, defined as the range at which at least $x\%$ of the read attempts are successful (x set to 10 in our experiments). This metric helps to conservatively estimate the read range by accounting for variations over time (due to multipath fading, for example).
- *Read success rate*, defined as the ratio of the number of successful read attempts to the total number of read attempts. This metric is related to the first metric, read range, in the sense that threshold percentage of successful reads (x) used in defining the read range corresponds to a read success rate of $x/100$. This metric, read success rate, is referred elsewhere in the literature using different names (as response rate in [11] and as read rate in [8, 13]).
- *Reads per tag*, defined as the average number of successful reads per tag in scenarios with multiple closely spaced tags.

Besides the above metrics, we also report measured *read speed* (i.e., reads per second)[1] results from our experiments.

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[1] Note that read speed is referred to as read rate in [11].

Antenna	Type	Gain	Polarization
$A1$	Planar Inverted-F (PIFA)	3dBi	Linear
$A2$	Compact bent dipole	0.8dBi	Linear
$A3$	Directional flat panel	6-8dBi	Linear
$A4$	Directional flat panel	6.5-7dBi	Circular

Table 1: Different reader antennas used in the experiments.

Tag	Type
$T1$	Rafsec Gen2 Short Dipole Paper Tag
$T2$	A918 Universal Mounting Tag

Table 2: Two different tags used in the experiments.

3.2 Experiment Settings

For determining the feasibility of RFID-based mobile sensor data gathering applications, we focus on reader-tag communication, the core component of such applications, and carry out experimental characterization of read performance with the state-of-the-art RFID technology. Specifically, we consider RFID devices that communicate via far-field coupling and operate in the UHF bands (860-960MHz) as they not only can provide larger read range, but also are more effective in supporting scenarios with multiple closely spaced tags as well as transfer of larger amounts of data.

The UHF hardware used in our characterization study is compliant with the EPC Class1 Gen2 standard [3]. We use A528 compact reader from Caen RFID [7], an Italian supplier of UHF hardware. This reader is based on the new Impinj Indy R1000 reader chip [19], which combines multiple components into an integrated RFID circuit, enabling digital signal processing and analog data processing on the same chip. The result is smaller reader size (42 x 60 x 6.3 mm^3), making it suitable for use with handheld devices. Moreover, it complies with and can operate in both European (ETSI EN 302 208) and US (FCC part 15) regulatory environments. We experiment with four different antennas with the A528 reader differing in type, gain and polarization; these are summarized in Table 1. We consider two UHF passive tags summarized in Table 2. The first tag ($T1$) from UPM Raflatac [21] is a simple UHF label tag, which is a printed circuit enclosed in thin flexible plastic with a sticky back. The second tag ($T2$) from Caen RFID [7] also uses a dipole; it is according to the manufacturer “suitable to identify both metal and insulating objects and is in fact designed to be almost independent from the material where it is installed.”

In our experimental setup, the A528 reader mounted on A528DAT service board (providing power, USB and RS232 connections) is connected to a laptop over USB; it communicates with nearby tags (of either type shown in Table 2) via an antenna (from the set listed in Table 1). Note that we do not consider sensor or semi-passive tags, but it does not reduce the value of our study in assessing the feasibility of RFID-based mobile sensor data gathering applications because of two reasons. First, EPC Class1 Gen2 standard establishes a single UHF specification that can be easily extended to incorporate higher class tags while not conflicting with the operation of deployed tags. Note that semi-passive tags belong to class 3, whereas label tags used in our study ($T1$) belong to class 1. Second, our study using passive tags in essence indicates worst-case read performance because higher class tags with built-in batteries typically have a larger read range because of their battery-assisted backscatter capability. We also do not consider the reader-AP communication as it is relatively less challenging; communication over WiFi in indoor scenarios with pedestrian mobility has been well studied with a number of performance optimizations.

Most of our experiments were carried out in a laboratory environment, a typical indoor scenario. The size of the lab is approximately 6.25m x 7m. It has side benches against the walls all the way round the room with several computers on them and a large table in the middle of the room; some of the benches have underneath them cupboards as well as two metal cabinets in one corner. We used two functions provided by the software supplied with the reader to calculate the metrics (see Section 3.1) for our experimental

Tag Orientation	Read Range (cm)
Vertical	200
Horizontal	120

Table 3: Read range results for the baseline scenario — reader with antenna $A1$ communicating with tag $T1$ in free space.

characterization: (1) *single inventory*, which attempts to read a tag in range around 60 times; and (2) *start inventory*, which continuously reads nearby tags until stopped.

3.3 Results

3.3.1 Baseline Scenario and Impact of Tag Orientation

We begin our experimental characterization of UHF read properties by considering a baseline scenario. Specifically, we look at the communication between reader with antenna $A1$ (which is the default antenna that came as part of A528 reader development kit) and simple label tag $T1$ in *free space*. In this scenario, the reader antenna $A1$ is placed flat on the table in the middle of the lab and one $T1$ tag is also placed on the same table such that it is standing either vertically or horizontally propped up from behind by a folded piece of paper also standing on the table. The separation distance between the reader antenna and the tag on the table is varied to determine the read range. Table 3 shows the results, which clearly show the impact of tag orientation on read range — the read range when the tag is standing vertically and aligned with the electric field of the antenna is greater by more than 65% compared to the case the tag is standing horizontally. We also observed a steep fall effect — read success rate quickly drops to zero when the tag is moved further away from the reader antenna by a few centimeters.

3.3.2 Multiple Tags in Close Proximity

Results for the baseline scenario in the previous subsection suggest that read ranges in the order 1-2m are feasible, but that may not be acceptable for some sensing applications. One straightforward approach to supporting such applications is to lower the spatial resolution of sensing by requiring multiple closely located tags together to provide a sample rather than every individual tag. While this can be done relatively inexpensively due to the lower cost of tags, it also increases the likelihood of collisions between responses from tags that are close to each other in turn reducing the effective read range. We have carried out experiments to assess the impact of tag proximity on read range. Our experimental setup is similar to the baseline scenario involving reader with antenna $A1$ and $T1$ tags in free space, but now we have multiple (5) tags standing besides each other in a row; we vary the separation between adjacent tags from 0cm to 30cm. As can be seen from Figure 2, 30cm separation results in a range similar to the single tag scenario (see previous subsection), whereas no spacing between tags brings down the range by more than half. On the positive side, from the viewpoint of RFID-based mobile sensor data gathering applications, 30cm inter-tag spacing is low enough that it would be acceptable for most applications.

We have also considered the impact of number of tags and found that increasing the number of tags for a given inter-tag spacing has the effect of reducing the read range. For instance, we found the read range with 10 tags and 5cm spacing between adjacent tags to be 88cm, compared to 127cm with 5 tags and 5cm spacing shown in Figure 2. We also experimented with tags placed in a grid-like manner. The results from these experiments are qualitatively similar to the above where tags are placed in a row (linear arrangement). Another important observation from these experiments is that the read speed measured in our setting is around 150 reads/second, about one-third of the maximum read speed (450 reads/second) possible with the EPC Class 1 Gen 2 standard.

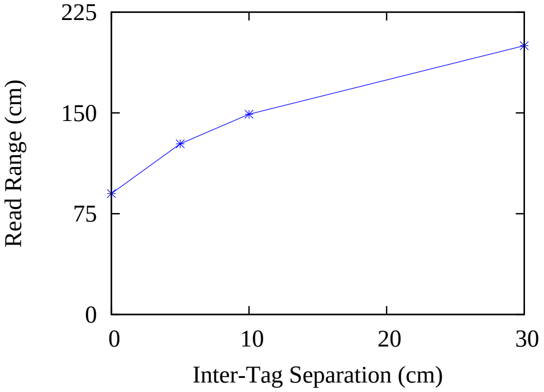

Figure 2: Impact of multiple closely spaced tags on read range. In this scenario, reader with antenna $A1$ is communicating with 5 vertically standing $T1$ tags separated from each other by different distances.

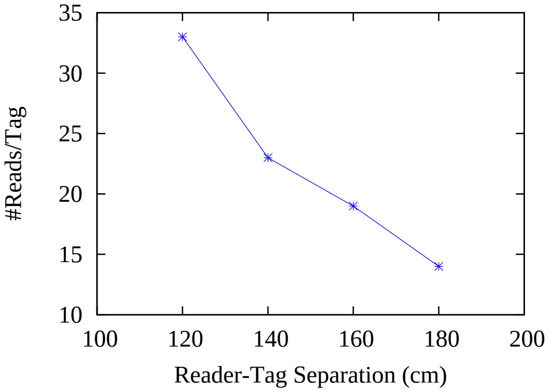

Figure 3: Read performance with a mobile reader with antenna $A1$ and $T1$ tags placed vertically in free space on a line parallel to the reader's path at walking speeds.

3.3.3 Mobility

In this subsection, we investigate a key issue for enabling RFID-based mobile sensor data gathering applications — the ability to read stationary tags from a distance using mobile readers carried by people moving at typical walking speeds (1m/s) in indoor scenarios. In our experimental setup, 5 $T1$ tags are placed vertically 30cm apart (based on the results from the last subsection) and the bottom end of each tag is stuck to the side bench such that much of the tag is visible from all sides (as if the tag was in free space). The experiment involved a person carrying the reader with antenna $A1$ walking on a line parallel to the side bench and separated by a distance d. We experimented with different values of d. A start inventory operation is begun at one end of the walk and it is stopped at a point where none of the tags could be read; this took around 2-3 single inventory cycles. Figure 3 shows the average number of reads per tag obtained from our measurements for distances that ensured at least 5 reads per each tag; each data point in the figure is an average over all 5 tags and 10 different walks. As expected, the number of reads per tag drops considerably as the distance d is increased. We also observed that the number of reads for different tags varies widely as d is increased. But more importantly, the tags can be reliably read while walking from a distance of up to 180cm, which is only 10% lower than the read range in a scenario with stationary reader and single tag (see results from baseline scenario). This is an encouraging result for RFID-based mobile sensor data gathering. In order to look at the impact of speed, we carried out some experiments with slower (faster) walking and found that it increases (reduces) readable distance compared to normal walking experiment as one would expect.

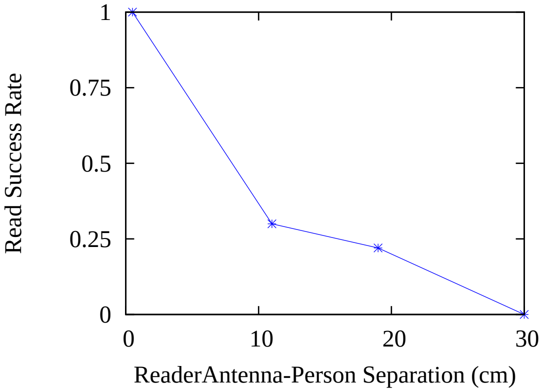

Figure 4: The impact of a person standing behind the reader antenna on the read success rate between reader with antenna $A1$ and tag $T1$.

3.3.4 People Effect

During our preliminary experiments with reader antenna $A1$, we happened to notice that the presence of a person behind the antenna seemed to increase the read range. To verify if a person nearby can benefit read performance, we have conducted a careful study as detailed below. Specifically, we placed the reader with antenna $A1$ at one end of the middle table in the lab and a vertically standing tag $T1$ is placed 207cm from the reader antenna towards the other end of the table propped up by folded piece of paper (as in the baseline scenario). The tag could not be read at all in this setup; it could be read if the tag is moved closer to 200cm as shown in Section 3.3.1. Now we did a single inventory cycle with a person standing 30cm behind the reader antenna, but it did not have any effect on the readability of the tag (i.e., read success rate was zero). When the person is moved closer by about 10cm closer to the antenna, the read success rate increased to 0.22. Moving the person closer by a further 10cm increased the read success rate by about 0.1. Finally, when the person was standing within 1cm behind the reader antenna, read success rate reached 1 (i.e., all read attempts were successful). Note that each data point is an average 10 separate measurements. These results plotted in Figure 4 clearly validate the fact the person standing behind the antenna can increase the read range because we could have moved the tag further away from the reader antenna until read success rate is just above 0.1 (the threshold defining the read range in our experiments) as the distance between the person and reader antenna decreased.

The literature on communication with body-worn antennas [22, 23] offers a plausible explanation for our measurement-based result. Proximity to human body can lead to high losses caused by bulk power absorption, radiation pattern fragmentation and antenna detuning, and that the impact of proximity to human body is dependent on operating frequency, antenna type and separation distance [22]. More importantly, results in [23] show that there are certain intermediate antenna-person separation distances where the power absorption is less and radiation pattern is deformed resulting in increased directivity (thus, increased directional range). Increasing the separation distance reduces the effect on radiation pattern, while decreasing it increases the power absorption. We conjecture that a similar phenomenon is taking place in our scenario although we could not bring the antenna too close to the human body (within few mm) due to limitations of our experimental setup. We have also observed that this effect is very much dependent on the antenna type. We observed a similar effect when person was standing sideways with antenna $A2$, whereas we did not notice any effect with antennas $A3$ and $A4$ (perhaps because they both are already directional).

3.3.5 Impact of Reader Antenna and Tag Types

So far, we have only considered one reader antenna type ($A1$) and one tag type ($T1$). In this subsection, we look at the read range performance in free space with different antenna and tag types summarized in Tables 1 and 2 respectively. Note that the directional antennas $A3$ and $A4$ are not suitable for use with mobile handheld devices; we use them only for comparison purposes. We use the same indoor lab environment as

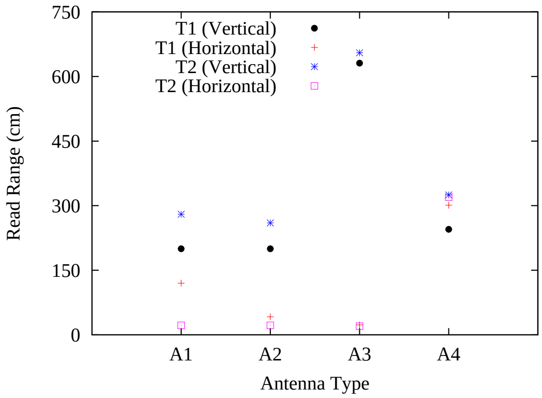

Figure 5: Read range performance with different reader antennas and tag types in free space within an indoor lab environment.

before. Results are shown in Figure 5. Note that we again include the results for read range with reader antenna $A1$ and tag $T1$ from Table 3 in Figure 5 for reference. Focusing on the results corresponding to antenna $A1$, we observe that the universal mounting tag ($T2$) can provide a read range of up to 3m when oriented correctly with respect to the reader antenna; this measured range is 25% lower than the number (4m) specified in the manufacturer's data sheet [7]. Also with antenna $A1$, tag $T2$ provides a 40% greater range relative to $T1$ if oriented correctly; otherwise it significantly reduces the range (by more than a factor of five) relatively. Comparing different linearly polarized antennas ($A1 - A3$), we see that the reduction in range due to tag misalignment is lower for $A1$ compared to the other two antennas. For these antennas, we also see that $T2$ is more sensitive to misalignment.

The circularly polarized antenna $A4$ is relatively immune to tag orientation problems as expected. We could achieve a similar effect with lower cost and relative ease by having two orthogonally placed tags act as a single high-level *dual-polarized* tag. In order to verify this hypothesis, we considered two tags of type $T1$ made to stand in a "L" shape on the table and interrogated by reader with antenna $A2$. We found the read range to be 104cm regardless of the relative reader antenna and tag orientation — when the antenna was vertical, the vertical tag was read and when horizontal, the horizontal tag was read. Comparing this result with those shown for antenna $A2$ and tag $T1$ in Figure 5, we see that the read range doubles with respect to the horizontal tag placement but halves relative to the vertical placement; the latter happens due to the collisions from having two tags next to each other without any spacing (see Section 3.3.2).

3.3.6 Other Results

We have conducted several other experiments to study the impact of height difference between readers and tags, different types of obstacles (cardboard box, plasterboard wall, wooden door, brick wall) and material surfaces (wood, metal). We briefly summarize these results below.

- *Height effect*: Our experiments with $T1$ tags and antennas $A1$ and $A2$ show that the read range obtained with reader and tag at the same height is valid so long as their height difference is less than 30cm.

- *Surfaces*: Moving from free space to placing $T1$ tags on a wooden surface tends to reduce the read range (by about 20-30% in most cases), whereas $T2$ tags are largely unaffected. Mounting tags on a plasterboard has the same effect as a wooden surface. Metal surfaces have a more detrimental impact — $T1$ tags when placed on a metal cabinet could not be read with antenna $A1$ from any distance even when standing vertically, whereas maximum read range reduced by 40% in the case of $T2$ tags.

- *Obstacles*: We find that cardboard box as an obstacle has no impact on the measured read range. On the other hand, when a tag $T1$ is mounted on one side of wooden door and read from the other side with antenna $A1$, the read range is within 20% of that obtained in free space. We found that

$T2$ tags, unlike $T1$ tags, are quite sensitive to the side from which they are read. Specifically, when read from the back side of the tag with a flat metal, the read range is halved in free space and even greater reduction is seen when the $T1$ tag is placed on a wooden surface with its back facing towards the antenna. When a tag was mounted on one side of a brick wall (acting as an obstacle) and read from the other side, read range obtained with $T1$ tags is similar to that with wooden surface and plasterboard. With $T2$ tags, however, read range is reduced significantly — halved when the front of the tag faces the wall, and reduced by a third otherwise.

3.4 Results Summary

In summary, our extensive characterization study shows that read range between 1-2m is feasible with current UHF RFID technology using compact readers and antennas, but it is dependent on a number of factors. In particular, tag orientation relative to the reader antenna has a big impact on the read range with linearly polarized antennas. Our "dual-polarized" tag approach offers an inexpensive and promising solution to reduce the impact of tag disorientation, which could be fairly common in practice. We find that with a reasonably small spacing between tags (10-30cm), multiple tags can be aggregated as a single high-level tag for applications requiring higher read range. Even more significantly, our results indicate that in mobile reader scenarios with typical walking speeds, read range reduction is only 10% compared to the static case. With some antennas, we find that the presence of person close to the reader antenna has a beneficial impact on the read range. Overall, from the viewpoint of RFID-based mobile sensor data gathering, these results are encouraging and show feasibility of such applications as people carrying mobile devices in typical scenarios would be walking along corridors (usually under 2m wide) with tags mounted on the side walls.

4 Related Work

In this section, we review the past studies on UHF RFID performance.

Nikitin and Rao [24] give an overview of factors that influence passive UHF RFID read range performance in theory, but do not discuss the performance seen in practice.

Ramakrishnan and Deavours [11] carry out an experimental evaluation of passive UHF RFID performance with the primary aim of providing a unbiased and reliable means to compare different RFID products or different classes of tags. Their evaluation focuses on scenarios where both reader and tags are stationary, whereas we are interested in read performance when readers are mobile. Their work is different from ours in a few other ways. First, read ranges in their work are studied indirectly via attenuation of reader transmit power levels while keeping reader-tag separation distance constant (at 1m); in contrast, we follow a straightforward, common and generic approach of using read rates to determine read range. Second, they focus on the impact of tag antenna radiation pattern, whereas we characterize the impact of polarization losses on read range for one common tag antenna type (dipole). Third, they compare tags belonging to different EPC classes (0 and 1), while we restrict ourselves to class 1 tags as sensor data gathering applications require the ability to write information to tags. Note that even though we experimented only with class 1 tags, our results are applicable to higher-class tags as well, especially semi-passive tags.

The same authors in their subsequent work [12] extend their evaluation to study other aspects such as near-metal and near-water read distances, frequency-dependence of read distance and near-field read distance, besides free-space read distances, in the context of supply chain applications. The use of fixed readers with high-power and high-gain directional antennas distinguishes their work from ours as we mainly focus on compact readers with low-gain antennas for use with mobile handheld devices.

In another recent work, Hodges et al. [13] investigate methods for better assessment of UHF RFID read range in the context of pervasive computing applications. In particular, attenuation-thresholding along with robotic automation are proposed as better alternatives compared to the commonly used read-rate based approach. However, this work does not consider mobile scenarios nor do the proposed methods naturally extend to scenarios where either the reader or tags are mobile. Additionally, we believe the smoothing effect seen from using attenuation-thresholding technique is largely due to the 2dB loss introduced by the attenuator as the transition from 100 percent read rates to 0 percent happens within just 4dB range [11], thus suggesting that read ranges predicted by this method tend to be more on the conservative side.

In concurrent work, Buettner and Wetherall [14] carry out a low-level measurement study of UHF RFID performance using a custom software radio based RFID monitoring system and configurable readers. Their results show the benefit of tuning the physical layer parameters and integrating the MAC and physical layers. These results are complementary to our work and only make the case stronger in favor of the RFID-based mobile sensor data gathering paradigm.

5 Conclusions

In this paper, we have proposed a class of low-cost and long-lived indoor sensing applications that gather data from densely deployed static RFID sensor tags using mobile devices equipped with RFID readers.We have also looked into the feasibility of such applications via a detailed experimental characterization study involving UHF RFID devices. Our results show that it is possible to obtain read range between 1-2m at walking speeds with current technology through careful planning, especially in terms of relative orientation of reader antennas and tags. Read range is also dependent on a number of factors including mounted surfaces and obstacles in the environment. Aggregating multiple tags into a single high-level tag from the application viewpoint has the dual benefit of compensating for shorter read ranges as well as dealing with tag disorientation. Overall, from the viewpoint of RFID-based mobile sensor data gathering, our results show feasibility of such applications. Our future work will focus on multi-reader scenarios and studying the behavior of end-to-end latency and data delivery reliability metrics.

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