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RELIABILITY TECHNIQUES FOR RFID

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ABSTRACT: *Radio Frequency Identification (RFID) technology has the potential to dramatically improve numerous industrial practices. However, it still faces many challenges, including security and reliability, which may limit its use in many application scenarios. While security has received considerable attention, reliability has escaped much of the research scrutiny. Radio Frequency Identification (RFID) technology is growing rapidly across many different industries. Developers apply the technology not only in traditional applications such as asset or inventory tracking, but also in security services such as electronic passports and RFID-embedded credit cards. However, RFID technology also raises a number of concerns regarding privacy and security.*

KEY WARDS: *Radio Frequency Identification (RFID) technology.*

1. Introduction

Radio Frequency Identification (RFID) technology is a wireless, automatic identification technology that uses radio signals to identify, track, sort and detect a variety of objects including people, vehicles and assets without the need for direct contact (magnetic stripe technology) or line of sight contact (bar code technology). RFID technology can track the movements of objects through a network of radio-enabled scanning devices over a distance of several meters.

2. Overview

The application of RFID technology requires RFID tags attached to objects and an infrastructure for reading the tags and processing tag information. The infrastructure typically consists of antennas, readers (each typically controlling 1 to 4 antennas), and a back-end system with edge servers, application servers, and databases. An antenna employs RF signal to activate the tag, which then responds with its data, typically a unique 96-bit identification code and some asset related data. The reader collects the data and forwards it to the back-end system. The back-end system implements the logic and actions for when a tag is identified. The logic can be as simple as opening a door, setting off an alarm, updating a database, or complicated, such as an integrated management and monitoring for shipment tracking.

2.1 Reliability: Definitions and Challenges

We define the read reliability as the probability that an RFID reader successfully detects and identifies an RFID tag when it is in the read range of one of the reader's antennas. Similarly, we define the tracking reliability of an RFID system as the probability that the system successfully detects and identifies an object when it is present in a designated area. Note that the system-level definition of tracking reliability obviates a one-to-one mapping between a tag and an object. For example, an object may carry multiple tags or a human may be identified indirectly based on tagged objects in his possession. In this paper, we will only consider the reliability of detection and identification of tags and/or objects, not the reliability of the individual system components or the actions taken by the system logic.

There are many factors that can impact read reliability, including the type of material surrounding a tag (e.g., metals or liquids), the inter-tag distance, the orientation of the tags with respect to the antenna, the tag-antenna distance, the number of tags in the read range of the antenna, and the speed of the tagged objects. Materials such as metals and liquids not only block the signal when the material is placed between the antenna and the tag, but may act as a grounding plate if the tag is too close to the material even if the material is not between the tag and the antenna. Tags placed too close to one another also interfere with each other's operation. The orientation of the tags, specifically, the orientation of the tag's antenna with regard to the reader antenna has a large impact on how much of the reader signal the tag is able to absorb. The number of tags in the read range of an antenna affects reliability because only one tag can be read concurrently but multiple tags may respond in a given read slot, causing collisions. State of the art RFID systems use sophisticated collision control mechanisms to reduce collisions. Finally, higher object speeds limit the time when tags are visible to an antenna.

RFID measurements are particularly prone to false negative reads, where a tag present in the read range of an antenna is not detected. In some cases, it is also possible to get false positive reads, where RFID tags might be read from outside the region normally associated with the antenna, leading to a misbelief that the object is near the antenna [3]. We focus on false negatives since false positives can typically be eliminated by increasing the distance be- tween antennas and/or by decreasing the power output of the readers.

Note that we do not consider intentional destruction of tags (e.g., removal of tag antenna [8] or removal of the whole tag), hiding of tags by shielding them, or interfering with the read protocol [7]. Furthermore, we do not consider modifications to the RFID protocol itself such as better collision control algorithms that can significantly improve reliability in multiple tag situations [9, 18].

2.2 Related work

Several recent pilot studies have evaluated the reliability aspects of RFID technology. A pilot study of a pharmaceutical supply-chain tracking system [1] observed read reliabilities ranging from under 10% to 100% for item-level and case-level tags in different stages of the shipping process. A performance benchmark [12] presented the results from number of experiments including read speed for a population of stationary tags and read reliability for different tagged materials on a conveyer belt. However, neither work attempted to develop techniques to improve reliability.

Other research efforts have proposed techniques to improve the reliability of RFID systems. In [10], the authors propose a cascaded tagging approach, where in addition to normal item level tags, the cases, pallets, and truckloads are tagged with ‘macro tags’. A macro tag provides information about the tags contained in the macro tagged collection. The macro tags are typically different from the item-level tags to make them easier to detect, for example, they may have larger antennas or be active tags. In this paper, we only consider techniques that use identical tags. In [17], the authors propose redundancy and diversity of antennas, readers, and tags, as methods to increase system reliability. Neither of these two efforts evaluates the effectiveness of their proposed techniques. Finally, in [6], the authors pro- pose to use real-world constraints to correct missed reads for tracking mobile objects. Specifically, they consider constraints related to possible physical movement paths of objects (‘route constraint’) and known groupings of tagged objects (‘accompany constraint’).

3. RFID Reliability Experiments and Results

To highlight the reliability challenge in current state of the art EPC Gen 2 RFID systems, we have conducted numerous experiments that reproduce various realworld situations in our lab using COTS components. We used single- dipole Gen 2 tags from Symbol Technologies, which had an antenna patch size of 2.5 cm by 10 cm. We used the Matrix AR400 reader along with a single area antenna. We used the default settings on the reader, which included a maxi- mum power output of 30 dB (1 watt). While our experiments consider only one type of tags, readers, and antennas, our results offer insights to (1) a number of important parameters impacting RFID system reliability, and (2) the effectiveness of system-level reliability techniques. We developed software in Java to interface with the reader. Our software sends commands to the reader over its HTTP interface and the reader responds with a list of tags in XML format. For all but the read range experiment, the readers were operated in a buffered (continuous) read mode and our tracking results were independent of the application level polling speed.

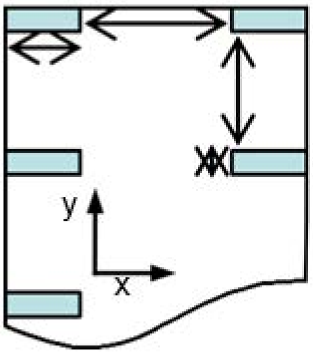

Fig. 1. Tag placement for read range exp

Read Range: The read range of RFID systems depends a lot on their operating frequencies. For the UHF systems we used, it is generally a few meters. To characterize the impact of the tag-antenna distance on read reliability, we placed 20 tags in a single plane, parallel to the antenna. The tag placement is shown in Figure 1. Inter-tag distances were 12.5 cm and 20 cm along the x and y axes, respectively. Our experiments showed that this distance is more than sufficient to eliminate direct interference between tags. The tags were fixed in position facing a single antenna, and a single read was performed each time. We repeated the read 40 times for each distance. Figure 2 shows the average number of tags read, and the upper and lower quartiles. Our results show a 100% read reliability at a distance of 1 m. However, reliability gradually dropped between 2 m and 9 m.

Inter-Tag Distance and Tag Orientation: In many practical scenarios, tags may be placed close to one other, in parallel, and/or in different orientations with regard to the antennas. To characterize the impacts of inter-tag distances and tag orientation with respect to the antenna, we performed multiple experiments using 10 tags in parallel to each other. We mounted the tags on a cardboard box, and used a cart to pass them in front of a single antenna with a speed of about 1 m/s and antenna-tag distance of 1 m. This represents a situation where items are carried by a conveyor belt through a gate.

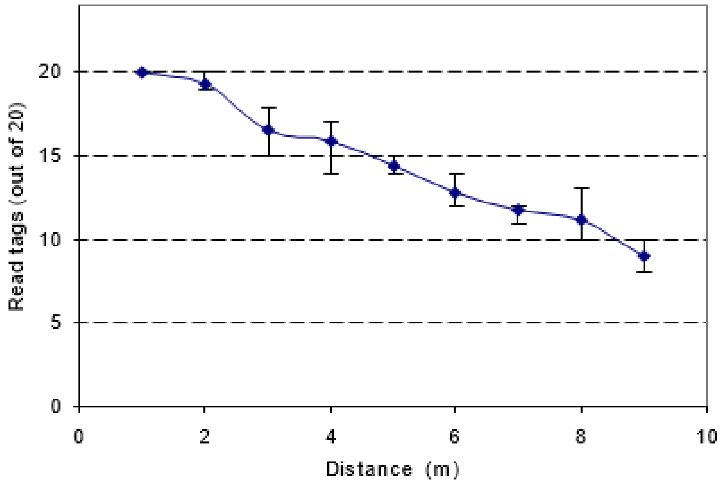

Fig. 2. Read reliability vs. antenna distance

We tested the combination of five different inter-tag distances: 0.3 mm, 4 mm, 10 mm, 20 mm, and 40 mm, and six different tag orientations (Figure 3). We repeated each experiment at least 10 times. Figure 4 shows the average number of tags read, and the upper and lower quartiles for each experiment. We are interested in finding the minimum 'safe' distance between tags where they will not interfere with each other. Our results show that, depending on orientation, tags require at least 20 to 40 mm spacing between them to operate in a reliable fashion. We can also see the effect of tag orientation. It is not surprising that tag reads are least reliable when the tags are perpendicular to the antenna (cases 1 and 5). Our results clearly indicate that current UHF tags would not work well for scenarios where tags are placed very close to each other and are perpendicular to the antenna, such as on book covers in a bookshelf.

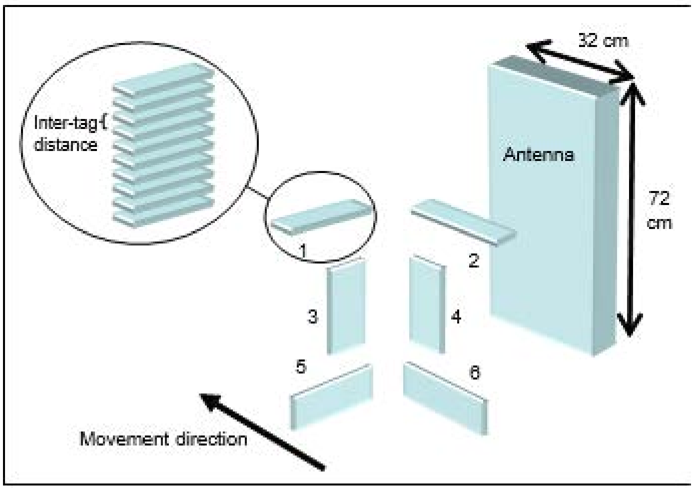

Fig. 3. Tag orientation and antenna

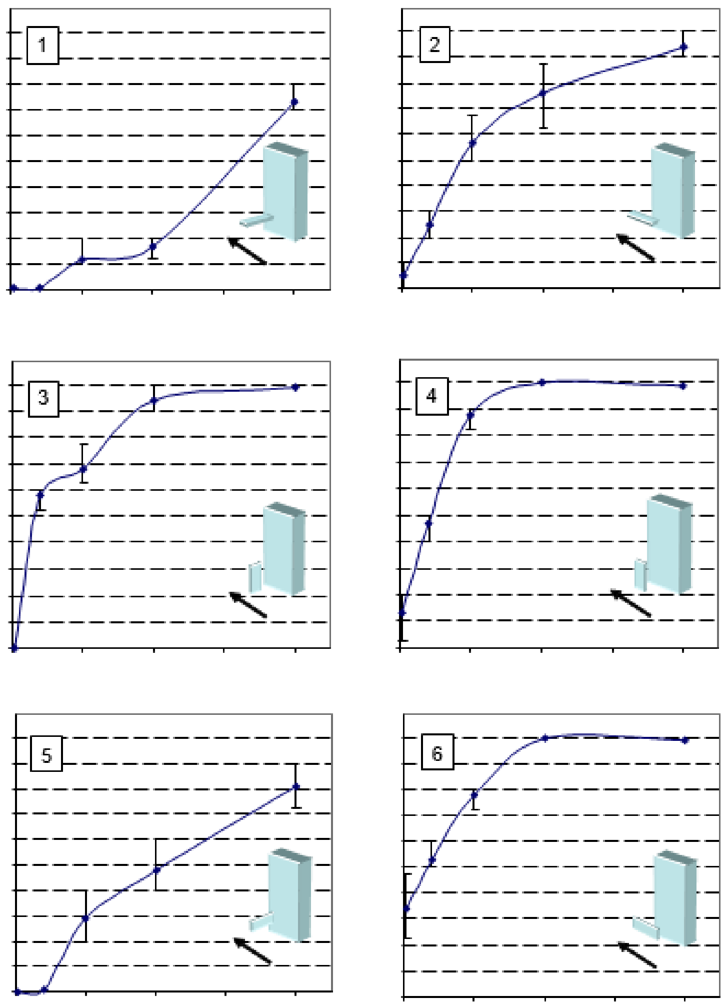

Fig. 4. Tag orientation and inter-tag distance

Object Tracking: In the previous experiments, the tags were not attached to any objects. However, in real world situations, tags are placed on objects that may interfere with RF signals. To measure RFID performance for realistic case level and item level tagging, we individually tagged 12 identical boxes, each containing a network router and accessories in original packaging. The metal casing and relatively large size of the routers compared to their packaging material would make them a challenging scenario for an RFID system. We placed the boxes on a cart as three rows of 2x2 boxes, and passed the cart in front of the antenna with a speed of 1 m/s at a distance of 1 m. We performed this experiment for different tag locations, namely top, front, side closer to antenna, and side farther from antenna. The experiments were repeated 12 times. Our results in Table 1 demonstrate that the location of a tag on an object has a dramatic impact on the tag read reliability. Assuming that tag read reliabilities are equal between the front and back of the box, and between the top and bottom of the box, the average read reliability for all locations is 63%. While guaranteeing the exact location of tags upon passing in front of a reader is impractical for many scenarios, it is often practical to avoid the worst locations (in this case, the top of the box). Our measurements show determining and avoiding the worst case locations can greatly improve average reliability. This is similar to the orientation tests, where two out of six orientations had considerably worse reliability.

Table 1. Read reliability for tags on objects

Tag location	Reliability
Front	87%
Side (closer)	83%
Side (farther)	63%
Top	29%
Average	63%

Human Tracking: One application of RFID systems is tracking humans. Active tags have been employed for human location sensing and tracking [11]. Passive RFID tags are currently in use for identification purposes in access cards and credit cards. We set out to evaluate the performance of passive RFID systems for human identification and tracking.

We experimented with multiple tag locations, and found that for best performance, tags and antennas should be at the same height, and tags should not touch the body. Therefore, we placed the tags at waist level, hanging from the belt or pocket, as often seen with ID cards, to achieve best performance. We placed a tag on one or two volunteers and they walked in front of an antenna at a distance of 1 meter. The volunteers tried to walk in parallel for the two person tests to maximize blocking. This could resemble a typical case for people with a RFID tagged ID card passing through a gate or doorway. It can also be used for human tracking with room-level accuracy. We tested with multiple tag locations. Each test was repeated 20 times. From the results in Table 2, the read reliability averaged 63% for one subject. Blocking by the closer subject caused the two subject read reliability to average 56%. Interestingly, read reliabilities for the closer subject in the two subject case was higher than those for a single subject. Further tests showed the reason was not the slightly closer distance. We attribute the higher read reliabilities to signal reflections off the farther subject. The low reliability in all of these cases motivates us to apply simple fault-tolerance techniques.

Table 2. Read reliability for tags on humans

Tag location	One subject	Two subjects		
		Closer	Farther	Average
Front / Back	75%	90%	50%	70%
Side (closer)	90%	90%	50%	70%
Side (farther)	10%	30%	0%	15%
Average	63%	75%	38%	56%

4. Improving RFID Reliability

We investigated the use of redundancy to improve the reliability of RFID systems and evaluated its effectiveness through both analytical analysis and experimental measurements. Redundancy in the form of replication is a widely used fault-tolerance technique for improving reliability. It can be applied to RFID systems in a number of ways: multiple antennas per portal, multiple readers per portal, or multiple tags per object.

Multiple antennas mounted per portal is a widely used technique and virtually all readers have built-in support for assigning two or more antennas to a single zone or portal. Even though readers employ measures such as TDMA to prevent interference between two or more of their antennas, our initial observations showed a slight decrease in performance when blocking was not an issue. Nonetheless, in realistic cases, there was a distinctive gain using multiple antennas. For multiple antenna tests, we used two area antennas placed at a distance of 2 meters from each other and connected to the same reader. While one might expect to see similar improvements for multiple readers per portal, our measurement clearly showed the opposite: read reliability was severely reduced in our experiments. The reason is reader-to-reader RF interference. While Gen 2 has standard measures to combat this problem, called dense-reader mode, it is optional for readers. Our readers did not sup- port dense-reader mode, and neither do most older Gen 2 readers.

While using multiple tags for each object seems straightforward, to the best of our knowledge it has not been evaluated before in scientific literature. Multiple tags on different sides of an object and/or with different orientations increases the probability that at least one of the tags is successfully read by a reader. However, if the tags are too close, they may interfere with one another and actually reduce the read reliability. Furthermore, if the number of tags in the antenna read area gets large, it can take considerably longer to read the tags.

We now use a simple analytical model for multiple tag and/or antenna scenarios. We define every combination of tag and antenna in the same area as a read opportunity. Assuming read opportunities are independent, if the reliabilities for read opportunities leading to an object identification are P1, P2, Pn, the expected object tracking reliability RC is:

$$RC = 1 - ((1 - P1)(1 - P2)...(1 - Pn))$$

We will next present our experimental results, and compare their performance with the analysis. All measurements and conclusions in this section are dependent on not exceeding the minimum safe tag distances measured in Section 3.3, and allowing adequate time for all tags to be read, which is around .02 sec per tag.

4.1 Reliable Object Tracking

To characterize the effect of reliability techniques for object tracking, we repeated the same experiment as in Section 3, while employing redundancy at different levels. We will present both the measured reliability RM and the expected reliability RC, where RC is calculated based on the read reliabilities measured in Section 3. We have investigated the following cases: two antennas per portal instead of one, two tags per object instead of one, and two tags per object and two antennas per portal. The results for all cases are shown in Table 3 and Figure 5. Our measurements show the performance of multiple tags per object is better than multiple antennas per portal, and very similar to the analytical model. Using two tags instead of one, we increased the average object tracking reliability from 80% to 97%.

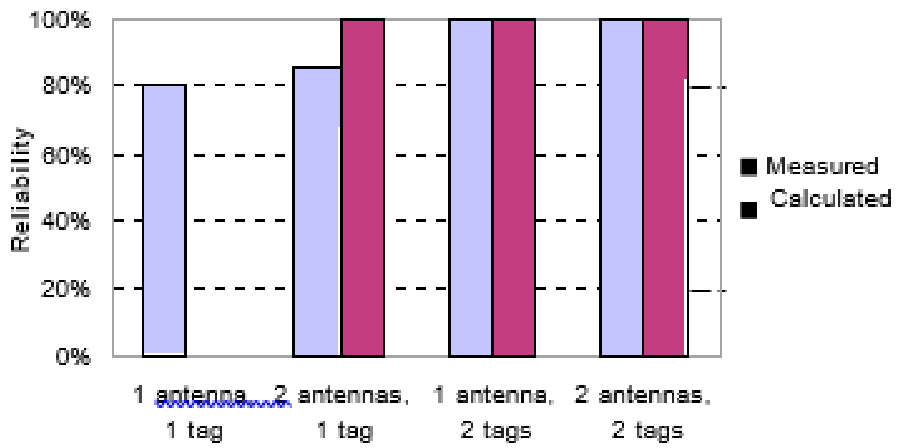

Fig. 5. Object tracking with redundancy

Table 3. Redundancy for multiple objects

Antennas	tags/ object	Tag location	Avg reliability	
			RM	RC
2	1	Front	92%	98%
2	1	Side	79%	94%
		Average	86%	96%
1	2	Front + side (good)	97%	98%
1	2	Front + side (bad)	96%	95%
		Average	97%	97%
2	2	Front + side	100%	99.9%

4.2 Reliable Human Tracking

To characterize the effect of reliability techniques for human tracking, we repeated the same experiment as in Section 3, while employing redundancy at different levels. We present both experimental results and expected tracking reliability for the combination of two antennas per portal, and two or four tags per person. The results for 1-antenna and 2-antenna cases are presented in Table 4 and Table 5 respectively. The average performances for one-subject and two-subject cases are shown in Figure 6 and Figure 7, respectively.

Similar to object tracking, the performance of multiple tags per person is better than multiple antennas per portal. Using two tags instead of one, increases average reliability from 63% to 96% for 1-person cases, and from 56% to 83% in 2-person cases. Reliability virtually reaches 100% using four tags per person or a combination of two tags per person and two antennas per portal.

We can clearly see that simple reliability techniques, especially using multiple tags per object, can significantly improve RFID system reliability to near 100%, even for applications that previously seemed out of the domain of passive RFID systems.

Table 5. Human tracking, 2 antennas

Tags per subject	Location	One subject		Two Subjects	
		RM	RC	RM	RC
1	Front/Back	80%	94%	90%	95%
1	Side	90%	91%	80%	78%
2	Front/Back	100%	99.6%	100%	99.8%
2	Sides	100%	99.2%	95%	97%
4	F/B/Sides	100%	100%	100%	99.9%

Table 4. Human tracking reliability, 1 antenna

Tags per subject	Location	One subject		Two Subjects					
				RM			RC		
		RM	RC	Closer	Farther	Avg	Closer	Farther	Avg
2	Front/Back	100%	94%	100%	90%	95%	99%	75%	88%
2	Sides	93%	91%	90%	50%	70%	93%	50%	72%
4	F/ B/Sides	100%	99.5%	100%	100%	100%	99%	88%	94%

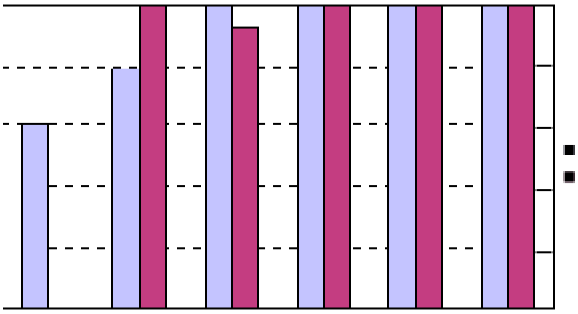

Fig. 6. Tracking of one subject

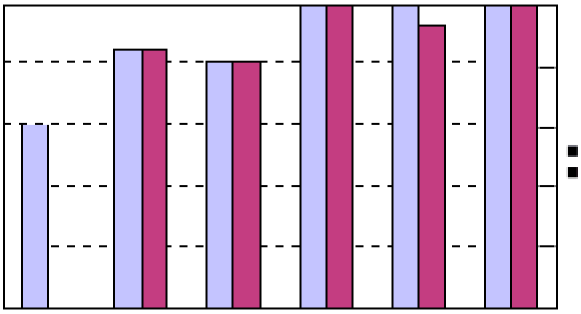

Fig. 7. Tracking of 2 subjects

5. Conclusion

In this work, we conducted extensive controlled measurements to characterize the reliability of passive RFID tags for tracking mobile objects and humans. Our measurements revealed critical insights into how reliability depends on various practical factors, such as inter-tag distances, lo- cation of the tag on an object, and tag orientation. To improve reliability, we explored simple and cost-effective reliability techniques, namely redundancy at the tag level, the antenna level, and the reader level. Our measurement clearly showed the high effectiveness of tag-level redundancy, followed by antenna-level redundancy, in increasing system reliability. Because our readers did not sup- port dense-reader mode, reader-level redundancy severely reduced reliability in our experiments, due to reader-reader interference. To the best of our knowledge, our work is the first that systematically characterizes the reliability of RFID systems and its dependence on various practical factors. Our results provide important guidelines for real-world deployment of RFID-based tracking applications as well as simple yet effective solutions to guarantee reliability. Future extensions of this work involve experimenting with active tags, and tag reliability for different tag designs.

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