Experimental Study on Mobile RFID Performance

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Abstract. An increasing number of applications use RFID in their design, but there is a lack of understanding of how mobility affects RFID performance in these applications. Unlike static RFID experiments, mobile RFID studies require more expensive equipment that are unavailable to most researchers. In this paper, we conduct machine-aided experiments to study the effects of mobility on RFID. Our results show that up to 50 RFID tags moving at speeds up to 2 m/s can be reliably read.

Keywords: RFID, mobility, experimental study.

1 Introduction

The prevalent application of RFID lies in industrial applications such as logistics and supply chain management. However, there has been considerable recent interest in applying RFID technology to non-industrial areas such as medical applications [2] and physical world object location [8,12]. Many of these ubiquitous computing applications differ from traditional industrial applications in their *unpredictability*, having to contend with objects moving at different speeds and times, take unpredictable paths, and contain different number of tags per item. These unpredictable factors make designing such systems difficult.

Given the expanding role of RFID technology into new areas, a deeper understanding of the capabilities of RFID equipment is crucial in designing new RFID systems. While there has been prior research on RFID performance in static environments, where both the reader and tag are stationary, there are relatively few academic research on the effects of mobility on RFID performance. One reason is that experiments on mobility are difficult to conduct. Meaningful experiments require performing the same experiment multiple times at the same speed and conditions as far as possible. This rules out human based testing where a person with some RFID tags tries to walk pass an antenna at approximately the same speed over and over again.

In this paper, we conduct experiments using commercial RFID readers and EPC Class-1 Generation-2 RFID tags, together with machine-aided testing, to

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examine the effects of mobility on RFID tags. As noted in [10] which used a robotic arm to perform extensive experiments on static tags, mechanical testing allows for tests that are otherwise impractical to conduct. Through this experimental study, we would like to show how a reader's reading behavior is like in a realistic mobile setting. We hope that this study could give researchers without access to the experimental equipment first hand experience and empirical understanding about the reading performance for mobile scenario.

Our main contributions in this paper are two fold. First, we conduct practical experiments to study the effects of mobility and RFID performance. As far as we know, most such experiments have been conducted by commercial vendors and the results are not widely available. Second, we plan to make publicly available all experimental data. This data will be useful for researchers interested in performing simulations for their own RFID projects. The rest of the paper is as follows. Section 2 reviews the related work. Section 3 explains our experimental setup, and Section 4 presents the results. Additional discussion of the findings are found in Section 5, and Section 6 concludes.

2 Related Work

Some earlier research efforts have focused on the RFID MAC layer. Work by [6] studied better techniques of selecting frame sizes to improve RFID reading performance, while [11] showed the effects of errors on reading performance. Other theoretical studies have looked at power modeling [9] for RFID systems.

Closer to our paper are real world RFID experimental studies. Fletcher et al. [5] examined the effects of different materials on RFID performance. Other work by [13,1] established performance benchmarks and performed speed and reliability experiments for static RFID tags. More recent work by [3] performed deeper analysis by utilizing specialized equipment to obtain physical layer RFID metrics such as error rates. Specific experimental studies on RFID and ubiquitous computing applications were done by [10,7]. In particular, [10] also used specialized equipment to perform extensive experiments that are difficult to perform. The main difference of our paper is that we focus extensively on *high speed*, *mobile* RFID experiments, while prior work focused mostly *static* experiments. The paper by [13] performed a limited experiment on a conveyor belt, but was limited to only 2 RFID tags. Extensive experiments utilizing a fast conveyor belt were performed by [14], but the experiments were limited to determine the best antenna placement position.

3 Experimental Setup

3.1 Hardware Used

All our experiments use the Alien-9800 reader and Alien-9610 linear antenna with a directional gain of 5.9dB. The 3dB beamwidth is 40 degrees. The RFID tags used are Alien 9540 general-purpose squiggle tags which support the EPC class 1 gen 2 standards [4].

The circular conveyor belt used to perform our experiments is approximately 18 meters long, with two parallel straight tracks each 4.4 meters long. The conveyor belt speed can be adjusted for speeds up to 2.0 m/s. A sketch diagram of the setup is shown in Fig. 1.

We mount the RFID tags on cardboard boxes, and placed the boxes on the conveyor belt track. This setup mimics a reader scanning a carton of items, where each item has an individual RFID tag. In all our experiments, we attached each RFID tag 4 cm away from each other. Each box is propped up so that the RFID tags are directly facing the antenna. We place each box on the conveyor belt at approximately equal distances from each other, making sure that at any one time, only one box is within the antenna's range. We use a total of 4 boxes, A B C D, in the experiments. The tag IDs for box A are labeled A1 to A10, IDs for box B as B1 to B10, and so on. Fig. 2 depicts our setup.

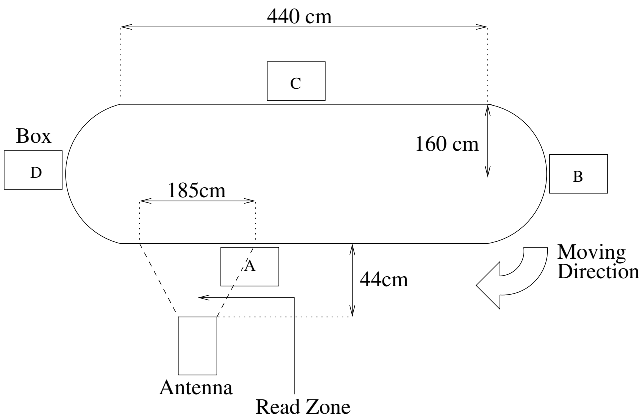

Fig. 1. Indoor conveyor belt

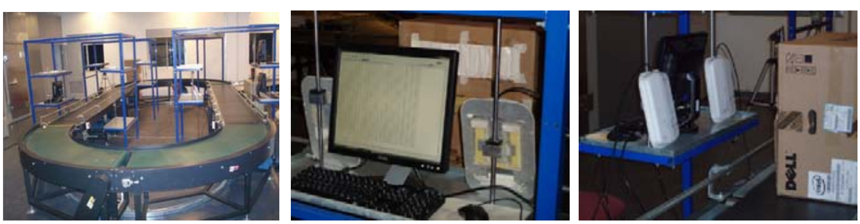

Fig. 2. Conveyor belt testbed. The picture on the left shows the entire route. The center photograph shows the position of antenna by the side of the track, and the rightmost photograph shows a box moving along the track.

3.2 Testbed Setup

One difficulty in setting up an RFID experiment lies in controlling the range of the antenna. To illustrate, we conduct a static experiment by placing some

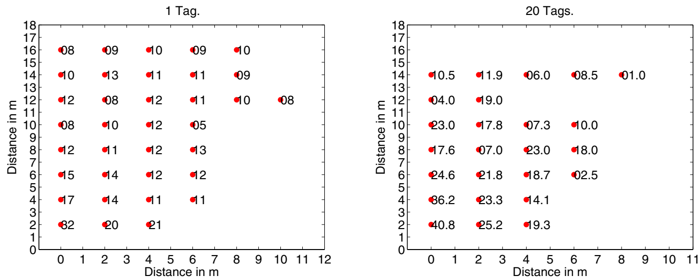

Fig. 3. Average number of times a tag is read at different locations

RFID tags in the middle of a large, empty room. We plotted a grid on the floor of the room, with each grid point two meters away from the other. We then place the antenna at each grid point, and set the reader to read for 30 seconds. Fig. 3 shows the results.

Each dot represents a grid location where at least one tag was read. The RFID tags at placed at position (0,0). The number corresponding to each dot is the average number of times an average tag is read at that location. We see that we can read some RFID tags even at distances of up to 14 meters away.

This large reading range makes it easy for accidental interference when conducting the experiments. We want to prevent the antenna from reading the boxes that are on the *opposite* track, i.e. preventing tags from box C from being read while box A is in front of the reader. We also want to prevent boxes that are along the curved portion of the track from being read as well.

Prior to an experiment, we first determine the reader's attenuation level. We position a box on the opposite track and reduce the attenuation of the antenna until the tags on the opposite track cannot be read. We determine that setting the reader attenuation at 15 dB is sufficient for our conveyor belt. Next we determine the extent of the reading zone by placing an RFID tag directly perpendicular to the antenna, and set the reader to read for 15 seconds, recording the number of times the tag is read. We then shift the tag to the next location several centimeters away, and performed the same test again until we reach a location where we get no tag reads.

3.3 Reader Settings

The RFID reader provides two methods for reading tags, *interactive* mode, and *autonomous* mode. In the interactive mode, a user will issue a command for the RFID reader to begin reading tags. Otherwise, the reader remains silent even if there are tags in the reading zone. In the autonomous mode, the reader is programmed to *constantly* try to read for tags. The reading process is triggered when a tag enters into the reading zone of an antenna. The advantage of using the autonomous mode is that it is easier to manage complex operations with multiple antennas since reads will automatically be performed when an object enters into the range of any antenna. We use the autonomous mode in our experiments to avoid manually triggering the read command.

We use the default setting for AcqG2Select where the reader issues a Select command once per cycle. From the manual, it appears that this command sets inventory flag of all tags to A at the beginning of the cycle. We also use the default AcqG2Session setting 1, which uses S1 session. In this session, each tag maintains its inventory flag between 500 ms and 5 s. In the experiments, the reader was able to read the tags fast enough that the persistent time of the inventory flag did not matter. However, we stress that in our experiments, the tags were always facing the reader's antenna with no other sources of interference. In an actual environment where it is more difficult to read the tags, the choice of session parameter may be important. The default modulation mode used by the reader is the Dense Reader Mode (DRM). This has a reader-to-tag data rate of 26.7kbps, and a tag-to-reader rate of 62.5kbps [3].

The reader has three parameters that will affect read performance, *cycle*, *round*, and *Q*. The *Q* parameter controls the frame size used to read the tags. In our experiments, the value of Q is 3. The *round* parameter determines the number of times we send send Q frames over to the tags, and the *cycle* parameter sets the number of times we execute the *round* parameter. In our experiments, the *round* parameter is set to 5, and the *cycle* parameter to 1. These are the default values for the reader.

4 Experimental Results

We ran read experiments using tag densities of 1 tag per box and 10 tags per box, and considered movement speeds of 0.5 m/s, 1.0 m/s, 1.5 m/s, and 2.0 m/s. We restrict the highest tested speed at 2.0 m/s due to the limitation of the conveyor belt. For instance, we tested the RFID performance at speed 2.0 m/s using 1 tag and 10 tags respectively.

For each experiment, we set the speed, and then turn on the conveyor belt. As the belt is moving, the RFID reader is set to continuously attempt to read. The

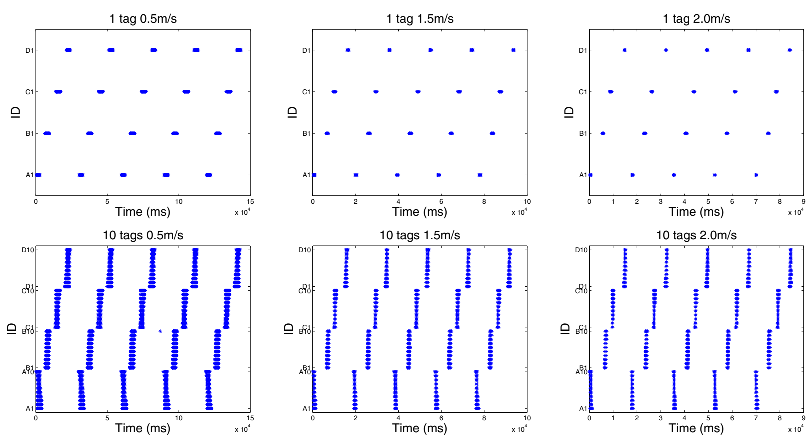

Fig. 4. Results for 1 tag and 10 tags for 5 rounds around the conveyor belt

boxes are left to run for 5 rounds, where each round is defined as all 4 boxes, A,B,C, and D have passed by the antenna once. We plot the time when each tag ID was read for all five rounds in Fig. 4. (The results for 1.0m/s are omitted due to space reasons). From the figure, we can clearly see the beginning and end of each round, and when each box enters and exits the reading zone. Fig. 5 shows a close up of one round.

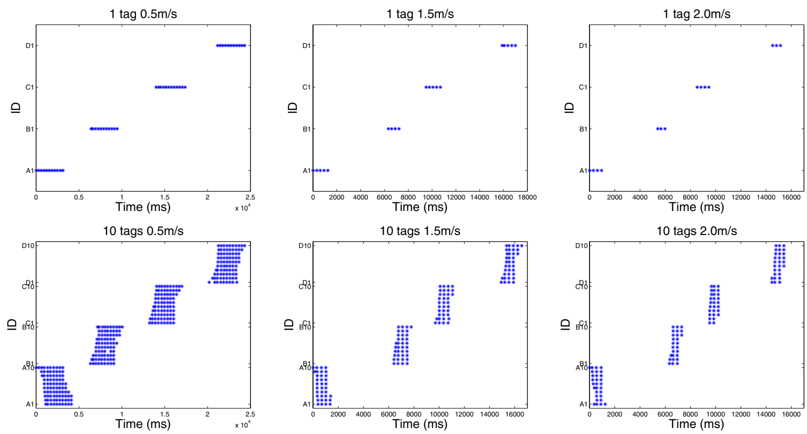

Fig. 5. Detailed results for one round around the conveyor belt. We can clearly see when each box enters and leaves the reading zone.

A popular metric for RFID performance is the number of reads performed per second. We can derive the reads per second for different speeds by

$$\text{Reads per second} = \frac{\text{Total number of reads}}{\text{Total reading time}}.$$

Unlike static experiments, we would like the total reading time to be the amount of time which the tags could *potentially* be read, rather than the total amount of time to complete the experiment. As seen in Fig. 5, there are gaps when a box has left a reading zone but another box has not entered the zone. We found that these gaps were unavoidable if we wanted to allow only one box in the reading zone at a time.

Instead, we define the total reading time as

$$\text{Total reading time} = B \cdot R \cdot T.$$

where B is the number of boxes used, R is the number of times a box passes the RFID reader, and T is the amount of time a box spends in the reader's reading zone. Since we know the length of the reading zone, and control the speed of the conveyor belt, we can determine the value of T any given speed. This total reading time is thus the amount of time in which tags could theoretically be read by the antenna. We plot the reads per second for various speeds in Fig. 6.

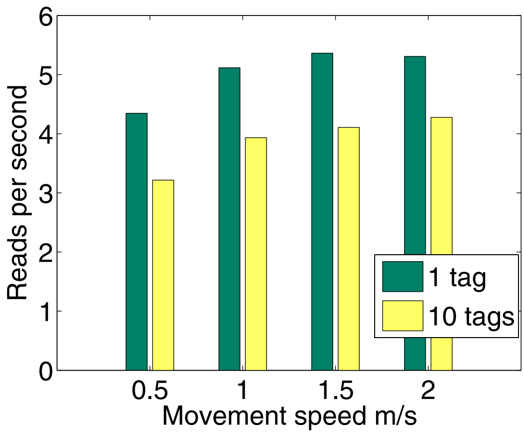

Fig. 6. Average number of reads per second for an average tag at different speeds

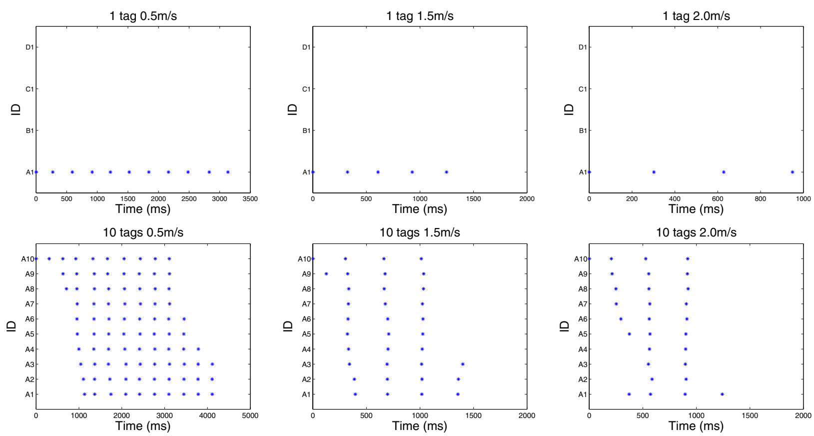

Fig. 7. One box entering and leaving the reading zone at different speeds

In the stationary case, the reads per second for a single tag and 10 tags is 3.11 and 1.716 respectively.

We see that as the speed increases, the reads per second increase as well. This is unexpected since the faster the tags move, the less time they spend in the reading zone, and thus should result in lesser number of reads.

To examine why faster speeds lead to more reads per second, we plot the results for one box with 10 tags entering and leaving the reading zone at different speeds in Fig. 7.

We see at time 0 ms, a tag enters the reading zone of the antenna, and the RFID reader begins reading for tags. Initially, there are fewer than 10 tags within the reading zone, thus there is only 1 tag being read. As the box moves further into the reading zone, more tags enter the reading range, and we begin to see all

10 tags being read. From the figure, we see that tags are read in orderly "groups" rather than individually tags randomly.

For instance, looking at the 1.5 m/s graph (center graph in Fig. 7), there are 6 distinct groups. The first group occurs at time 0 ms, and consists of only reading one tag, A10. The second group also consists of just a single tag, A9. In the third, fourth and fifth group, we see that all 10 tags are read. Finally in the sixth group, only three tags are read. We refer to one group as a single *read*. From the experimental data, we see that the time between two reads is approximately 300 ms regardless of the moving speed.

This partly explains why the reads per second increase as the moving speed increases. Looking at 1 tag moving at 0.5 m/s in Fig. 7, we see that in the first 1000 ms, the tag is read four times, and between 1000 ms and 2000 ms, the tag is read three times. We can compare this against the 1 tag moving at 2. 0m/s. In that experiments, the tag is also read four times in the first 1000 ms before leaving the reading zone. As a result, the reads per second for the 2.0 m/s is better than the 0.5m/s speed partly due to the wait in between two reads.

In the 10 tag experiments, we see that at slow speeds, the first few reads do not read all 10 tags, possible since the tags may not have entered the center of the reading zone where read performance is optimal. In the 10 tags 0.5 m/s results (left center graph in Fig. 7), the first three reads do not capture all the tags, where as in the 2.0 m/s results, we already capture all the tags within the first three reads.

5 Additional Discussion

Mobility Recommendations: The results shown above suggest that *continuous reading* tags may not be a good strategy due to the time lag in between reads. Instead ,the reader should try to estimate when the tags will be close to the center of the reader's antenna before attempting the next read. In Fig. 7, this occurs between the 1000 ms and 3000 ms when the speed is 0.5m/s. In the 1.5 m/s and 2.0 m/s speeds, the best opportunities to read lie between the 500 ms and 1000 ms mark. A careful issuing of read commands will also reduce overall interference since other readers in the vicinity cannot issue commands if the current reader is broadcasting. In addition, this information can be incorporated when cleaning the RFID data. Given an estimated movement speed, we can estimate which tag readings best represent the actual tags.

Detailed Look: Recall that we set the cycle parameter to one, the round parameter to five, and the Q value to three. Here, we wanted to see if we could determine how many tags were read in each round. The goal was to determine whether we could use a different round parameter to improve performance. We plot the data for a single read in Fig. 8. From the figure, we could not determine individual rounds from the data. We could only estimate that the time taken to read a tag is between 2 and 6 ms. There does not appear to be a pattern regarding the order of tag reads even though the plots depict the same box. This is probably due to the different random number used in each read.

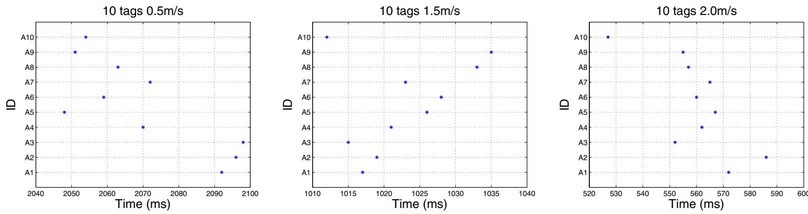

Fig. 8. One cycle at different speeds

Read Failures: One of the original goals of the experiment was to determine the reliability of reads at high speeds. Here we conduct an experiment with a denser number of tags. We place a total of 50 tags on a single box, and place the box on the conveyor belt to run for 5 rounds. The plot of when each tag is read is shown in Fig. 9.

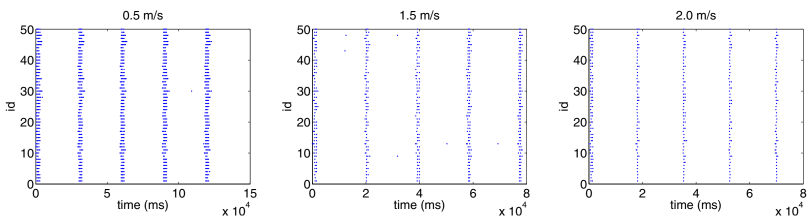

Fig. 9. 50 tags on a single box moving 5 rounds around the conveyor belt

We originally expected to be unable to read all the tags on a box at faster speeds because the box spends less amount of time within the reading zone. Also, faster movement might results in fading effects which will also impact performance. Unfortunately, as shown in the dense tag experiments, we were able to read all 50 tags traveling at the highest speed possible. One possible reason is that the reader's antenna is placed too close to the RFID tags (44 cm away) for noise resulting from fast movement to be a factor. Future experiments with greater distance between reader and tag are needed to examine this issue.

6 Conclusion

In this paper, we conducted experiments to determine the effects of mobility on RFID performance. We show that at a short reading range and a moving speed of 2.0 m/s, the reading capacity of 50 tags is achievable, showing that passive RFID tags can be used in pervasive computing applications for tracking people instead of more expensive sensor mote devices.

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References

1. Aroor, S., Deavours, D.: Evaluation of the state of passive UHF RFID: An experimental approach. IEEE Systems Journal 1 (2007)
2. Arumugam, D.D., Gautham, A., Narayanaswamy, G., Engels, D.W.: Impacts of RF radiation on the human body in a passive wireless healthcare environment. In: IEEE Conference on Ambient Persuasion in Pervasive Healthcare (2008)
3. Buettner, M., Wetherall, D.: An empirical study of UHF RFID performance. In: MobiCom 2008 (2008)
4. EPCglobal. Class 1 generation 2 UHF air interface protocol standard version 1.0.9
5. Fletcher, R., Marti, U., Redemske, R.: Study of UHF RFID signal propagation through complex media. In: IEEE Antennas and Propagation Society International Symposium (2005)
6. Floerkemeier, C.: Transmission control scheme for fast RFID object identification. In: PercomW 2006 (2006)
7. Floerkemeier, C., Lampe, M.: Issues with RFID usage in ubiquitous computing applications. In: Ferscha, A., Mattern, F. (eds.) PERVASIVE 2004. LNCS, vol. 3001, pp. 188–193. Springer, Heidelberg (2004)
8. Guinard, D., Baecker, O., Michahelles, F.: Supporting a mobile lost and found community. In: MobileHCI 2008 (2008)
9. Hawrylak, P.J., Cain, J.T., Mickle, M.H.: Analytic modelling methodology for analysis of energy consumption for ISO 18000-7 RFID networks. In: IJRFITA 2007 (2007)
10. Hodges, S., Thorne, A., Mallinson, H., Floerkemeier, C.: Assessing and optimizing the range of UHF RFID to enable real-world pervasive computing applications. In: LaMarca, A., Langheinrich, M., Truong, K.N. (eds.) Pervasive 2007. LNCS, vol. 4480, pp. 280–297. Springer, Heidelberg (2007)
11. Kawakita, Y., Mitsugi, J.: Anti-collision performance of Gen2 air protocol in random error communication link. In: SAINTW 2006 (2006)
12. Nemmaluri, A., Corner, M., Shenoy, P.: Sherlock: Automatically locating objects for humans. In: Mobisys 2008 (2008)
13. Ramakrishnan, K., Deavours, D.: Performance benchmarks for passive UHF RFID tags. In: MMB 2006 (2006)
14. Wang, L., Norman, B., Rajgopal, J.: Optimizing the placement of multiple RFID reader antennas to maximize portal read-accuracy. In: Technical Report 07-01, Department of Industrial Engineering, University of Pittsburgh (2007)