The Practicality of Multi-Tag RFID Systems*

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Abstract. Radio Frequency Identification (RFID) is an increasingly popular technology that uses radio signals for object identification. Successful object *identification* is the primary objective of RFID technology (after all, the last two letters of the acronym "RFID" stand for "identification"). Yet, a recent major study by Wal-Mart has shown that object detection probability can be as low as 66%. In this paper we address the fundamental issue of improving object detection by tagging objects with multiple tags. This confirms for the first time the practicality and efficacy of previous works on multi-tag RFID systems. Using different configurations of commercial RFID equipment, we show significant improvements in object detection probability as the number of tags per object increases. We compare various combinations of multi-tags, readers, and antennas, and demonstrate that adding multi-tags to a system can improve object detection probabilities more dramatically than adding more readers. We also address issues such as tag orientation and variability, effects of multi-tags on anti-collision algorithms and on object detection in presence of metals and liquids, as well as the economics of multi-tags.

1 Introduction

Radio Frequency Identification (RFID) uses radio communication to uniquely identify objects [1] [2] [3]. A typical RFID system consists of readers (sometimes called beacons), tags (sometimes called transponders), and back-end servers which receive and process the information that the readers collect from the tags [4] [5] [6]. There are two coupling mechanisms used by passive and semi-passive tags: inductive coupling and electromagnetic backscattering (i.e., far-field propagation). In inductive coupling the reader creates a magnetic field between itself and the tags which in turn derive power from this magnetic field. In far-field propagation the reader sends a signal to a tag and the tag backscatters (i.e., reflects) a response back to the reader. Some of the major applications of RFID include supply chain management, inventory tracking, access control, library book checkout, cattle tracking, passport tagging, and even games [7] [8] [9] [10] [11].

When bar codes are used for object identification, bar code scanners require line-of-sight visibility of the bar codes, and they usually must be close to the objects. Bar codes are scanned one at a time, and scanners need to physically move from one bar code to

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the next in order to read them. Since this is a mechanical process, the read rate is at best only a few bar codes per second. RFID readers on the other hand, can read hundreds of tags per second without a line-of-sight or mobility requirement, which allows easy automation of the reading process and makes RFID-based identification very appealing. However, as the identification process is automated, special care is required to ensure the detection of all objects within the reader's field.

Ubiquitous background radio noise impedes RFID object detection. Moreover, metals and liquids tend to reflect and/or absorb radio signals, further degrading the reader's ability to achieve accurate and complete tag identification. Missed items, even at a relatively low rate of 1%, can result in large financial losses for stores that rely on RFID-enabled automatic checkout stations. This situation is real and serious, since milk, water, juices, and canned / metal-foil -wrapped (i.e., Faraday caged) goods are commonly stocked in markets. Practical experiments by Wal-Mart in 2005 showed 90% tag detection at case level, 95% tag detection on conveyor belts, and only 66% detection rate of individual items inside fully loaded pallets [12].

To reduce the percentage of undetected items, we recently proposed tagging objects with *multiple* tags [13], in contrast to previous works on RFID technology that assume only a *single* tag per object. Although multi-tags will cost slightly more than single tags, we experimentally demonstrate in this paper that multi-tags can be very beneficial for many applications where higher object detection rates are required. The benefits of attaching multiple tags per object include: (1) greater induced voltages/power aboard some of the tags, (2) increased tag-reader communication range, (3) larger tag memory per object, (4) enhanced security, and (5) improved overall detectability, availability, reliability, and durability of the system [13]. This paper presents the first-ever extensive experimental study that validates the efficacy of a multi-tag RFID system in practical scenarios.

2 Optimal Placement of Multi-tags

Based on our previous theoretical results for multi-tags, object detection improvement hinges on the expected grazing angle of the radio signal from the reader to the tag [13]. We performed angle analyses for two power transmission modes, inductive coupling and far-field propagation. Let β be the angle between the arriving signal's direction (i.e., the B-field) and the tag's plane. In the case of inductive coupling, the induced voltage aboard a tag is proportional to $sin(\beta)$, and for far-field propagation, the induced voltage is proportional to $sin^2(\beta)[14][13][1]$.

The first question is how to orient the tags relative to each other in order to maximize the expected grazing angle of the radio wave to one of the tags' antennas. We assume a uniform distribution for the signal arrival direction, since in many RFID applications the orientation of a tag's antenna to the arriving signal can be arbitrary (e.g., products in a shopping cart, RFID-tagged cell phones, etc.). In the case of a single tag, the tag can be positioned arbitrarily, since its orientation would not affect the expected (uniformly distributed) signal arrival angle. For two tags, it is optimal to position them perpendicular to one another in the x-y and x-z planes. Similarly, for three tags, we can position them pair-wise perpendicularly in the x-y, x-z, and y-z planes. For four tags, it

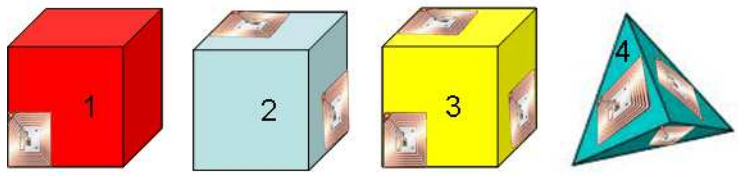


Fig. 1. Optimal multi-tag positioning for ensembles of 1, 2, 3 and 4 tags.

turns out that in order to maximize the expected signal incidence angle to at least one of the tags, it is best to position them parallel to the faces of a tetrahedron, a platonic solid[1](see Figure 1).

The second question asks what is the actual expected maximum grazing angle of the arriving signal with respect to the antennas of any of the tags, for a given tag ensemble. To answer this question, we computed the expected incidence angle analytically for one and two tags, and developed a software simulator that computes the expected angle for an arbitrary number of tags. The results indicate a two-digit increase in the expected grazing angle as we move from one tag to two tags, and also as we go from two tags to three tags, but only a 3 degree average improvement as we move from three tags to four tags. This suggests that adding an extra tag or two may be beneficial to dramatically improve object detection, but attaching the fourth tag to an object may not garner substantial detection probability improvement. These improvement trends are indeed corroborated by our experimental results discussed below.

Many objects are box-shaped, allowing multi-tags to be positioned perpendicular to each other, but even irregular-shaped objects can benefit from multi-tags, as demonstrated by our experiments. RFID tags are available in many shapes and sizes, making it feasible to attach multiple tags to any object.

3 Experimental Equipment and Setup

We performed our experiments using commercial FCC-compliant equipment, namely Ultra High Frequency (UHF) readers from Alien Technology (model ALR-9800, four antennas, multi-protocol, 915 MHz) and ThingMagic (model Mercury 4). We deployed sets of linear and circular antennas from Alien Technology, and circular antennas from ThingMagic. A single Alien Technology reader antenna can either broadcast or receive signals, whereas the more versatile ThingMagic antenna can both send and receive signals. We used several types of tags from UPM Raflatac, the world's leading RFID tag manufacturer. In particular, we chose unipolar UPM Rafsec UHF tags "Impinj 34x54 ETSI/FCC" and bipolar UPM Rafsec UHF tags "Impinj 70x70 ETSI/FCC" for our experiments.

[1] For five or more tags, it becomes more complicated to analytically determine the optimal relative positioning of the tags, except for specific special cases, such as for N=6 where the tags should ideally be placed parallel to the faces of a dodecahedron, and N=10 where the tags should be parallel to the faces of an icosahedron.

The experiments were conducted in an otherwise empty room, in order to minimize radio reflection / interference anomalies. We multi-tagged a diverse set of 20 objects[2] using four tags per object. We positioned tags perpendicular to each other whenever possible, and spread the tags far apart in space in order to minimize tag occlusion by other tags and/or objects.

We first describe our experiments involving the Alien Technology hardware, since this equipment allows us to collect data for both circular and linear antennas. A similar experimental setup was used with the ThingMagic equipment. In the discussions below, we will implicitly assume that the Alien Technology equipment was used in each experiment, unless explicitly stated that the ThingMagic hardware was used instead. Similarly, all the experiments discussed below have used the unipolar UPM Rafsec UHF tags "Impinj 34x54 ETSI/FCC", unless explicitly stated that bipolar tags were used.

We positioned Alien Technology reader antennas side-by-side in pairs, with each pair consisting of a sending and a receiving antenna. In one experiment we used linear antennas, and in the other experiment we used circular antennas. We positioned each pair of antennas 55 inches from the center of a plastic bag containing all 20 objects, 20.5 inches above the floor, and perpendicular to the bag. The reader was operating in "inventory mode" using Gen-2 tag reading protocol. We allowed sufficient time for the reader to read all the tags within its range by performing many tag reads and maintaining adequate timeouts between reads to make sure that the effects of the environmental noise are minimized[3].

We randomly (re)shuffled the tagged objects multiple times to change the tags' orientations with respect to the reader's antennas in order to improve the statistical significance of the results (the values reported in the tables and graphs below are *averages* over all object shufflings). We also varied the power emitted by the antennas, keeping in mind that the distance at which tags can be detected is proportional to $\sqrt{\mathrm{power}}$. We performed our experiments for linear as well as for circular antennas using 7 different power levels ranging from 25.6dBm to 31.6dBm, in increments of 1dBm.

4 Experimental Results

4.1 Linear Antennas

Our experiments show that multi-tags considerably improve object detection probabilities for linear antennas. The detection probabilities for different numbers of tags per object, different numbers of reader antennas, and various reader power levels are summarized in Figure 2. This table shows that switching from one to two tags per object produces a high double-digit increase in tag detection probability, and a low double-digit increase when moving from 2 to 3 tags, but only single-digit increase from 3 to 4 tags. These results corroborate our theoretical expectations [13].

[2] The multi-tagged objects included soap bars, cereal boxes, paper plates, plastic boxes, packaged foods, clothing items, etc.

[3] To enable others to reproduce our results, we specify here the Alien Gen-2 algorithm parameter settings used in our experiments: TAG_TYPE = 16, ACQ_G2_CYCLES = 10, ACQ_G2_COUNT = 100, ACQ_G2_Q = 2. Our source codes and scripts are available upon request.

	Antenna Pair #1				Antenna Pair #2				Antenna Pairs #1 and #2			
	1 Tag	2 Tags	3 Tags	4 Tags	1 Tag	2 Tags	3 Tags	4 Tags	1 Tag	2 Tags	3 Tags	4 Tags
Power: 31.6 dBm	0.5800	0.7930	0.8945	0.9385	0.5715	0.7970	0.9010	0.9570	0.6495	0.8450	0.9300	0.9695
Power: 30.6 dBm	0.5280	0.7500	0.8575	0.9070	0.4730	0.6980	0.8210	0.8950	0.5890	0.7970	0.8930	0.9380
Power: 29.6 dBm	0.4645	0.6895	0.8110	0.8760	0.4220	0.6545	0.7925	0.8885	0.5370	0.7555	0.8635	0.9195
Power: 28.6 dBm	0.4140	0.6360	0.7645	0.8390	0.4350	0.6615	0.7920	0.8695	0.4920	0.7155	0.8295	0.8880
Power: 27.6 dBm	0.3425	0.5435	0.6770	0.7645	0.3765	0.5940	0.7340	0.8200	0.4380	0.6620	0.7880	0.8565
Power: 26.6 dBm	0.3275	0.5345	0.6740	0.7695	0.3235	0.5255	0.6635	0.7580	0.3985	0.6195	0.7540	0.8380
Power: 25.6 dBm	0.2575	0.4410	0.5790	0.6895	0.2785	0.4615	0.5825	0.6580	0.3430	0.5565	0.6975	0.7880

Fig. 2. Detailed statistics showing the average detection probability for *linear* antenna(s) as a function of the power level for different antenna configurations and for different numbers of tags per object.

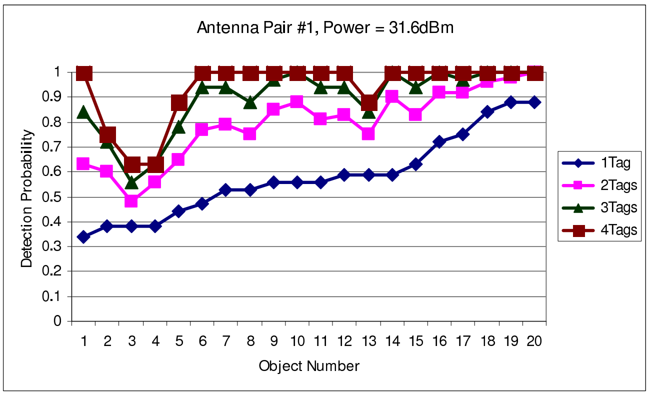
Figure 3(a) graphically shows the increase in object detection probability for each object (the objects are sorted along the X-axis according to their detection probabilities). Again, we observe significant separations between the first three curves. In Figure 3(b), we compare object detection improvements between two tags per object versus two reader antennas. From this data we can see a dramatic double-digit improvement from adding a second tag to each object, and only a low single-digit improvement from adding a second reader, yielding almost a factor of 4 improvement in object detection probability using multi-tags as compared to multi-readers.

4.2 Circular Antennas

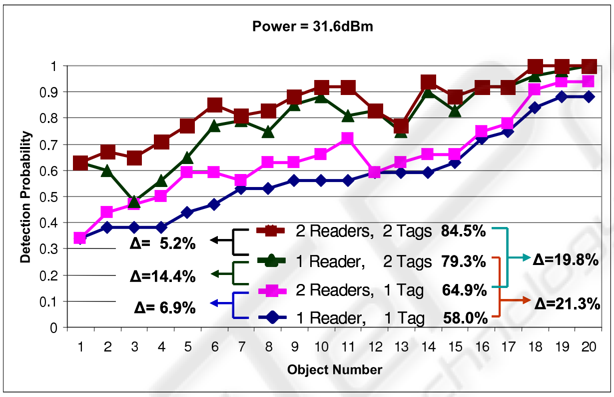
The detection probability statistics for circular antennas are given in Figure 4. As with linear antennas, experiments with circular antennas show a dramatic double-digit average improvement in object detection as the number of tags per object increases. However, the detection probabilities for circular antennas are higher than for linear ones, since the orientation of objects with respect to the reader antennas varies widely. From the comparisons of different numbers of multi-tags and multi-readers (Figure 5), we can see that for circular antennas the advantage of adding a tag is on par with that of adding a reader. Figure 6 gives two graphs that depict changes in object detection probability as a function of power for various multi-tag combinations. The graphs show that the average object detection probabilities decrease more rapidly for circular than for linear antennas, as a function of decreasing antenna power.

5 Importance of Tag Orientation

One of the major claims made in our original theoretical paper on multi-tags [13] is that tags need to be oriented perpendicular to each other to obtain the most benefits in object detection. Here we experimentally confirm this claim by varying the tag orientation, collecting tag identification data, and calculating object detection probabilities for different multi-tag orientations. We performed experiments with unipolar tags (UPM Rafsec UHF tag Impinj 34x54 ETSI/FCC) whose plane orientation matters, and with bipolar tags (UPM Rafsec UHF tag Impinj 70x70 ETSI/FCC) whose plane orientation has no effect on tag detection.



(a) Comparison of multi-tags



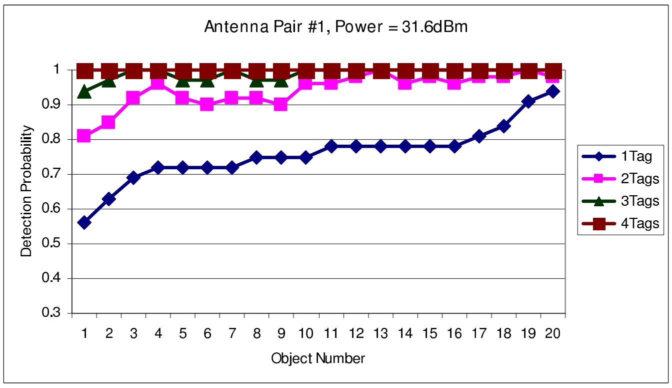
(b) Multi-tags versus multi-readers

Fig. 3. (a) Average object detection probability improvements for *linear* antennas as the number of tags per object increases. (b) Comparisons of multi-tags with multiple readers for *linear* antennas. Note that attaching multiple tags to an object yields higher average object detection probabilities than adding more readers.

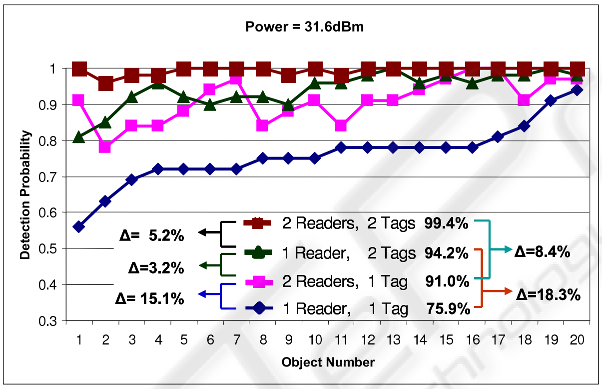
	Antenna Pair #1				Antenna Pair #2				Antenna Pairs #1 and #2			
	1 Tag	2 Tags	3 Tags	4 Tags	1 Tag	2 Tags	3 Tags	4 Tags	1 Tag	2 Tags	3 Tags	4 Tags
Power: 31.6 dBm	0.7595	0.9420	0.9895	1	0.6565	0.8745	0.9570	0.9880	0.9105	0.9940	1	1
Power: 30.6 dBm	0.7200	0.9225	0.9880	1	0.6515	0.8770	0.9630	0.9880	0.8875	0.9860	1	1
Power: 29.6 dBm	0.6675	0.8860	0.9710	1	0.5600	0.7830	0.8860	0.9270	0.8255	0.9660	0.9940	1
Power: 28.6 dBm	0.5710	0.8105	0.9215	0.9760	0.4790	0.7115	0.8335	0.8960	0.7460	0.9285	0.9785	0.9940
Power: 27.6 dBm	0.4560	0.6975	0.8305	0.9075	0.4460	0.6670	0.7970	0.8705	0.6400	0.8550	0.9345	0.9695
Power: 26.6 dBm	0.4075	0.6260	0.7585	0.8395	0.3380	0.5485	0.6810	0.7645	0.5375	0.7615	0.8615	0.9075
Power: 25.6 dBm	0.3050	0.5060	0.6355	0.7145	0.2870	0.4835	0.6205	0.7085	0.4430	0.6765	0.7985	0.8570

Fig. 4. The statistics table shows the detection probability for *circular* antenna as a function of the power level for different antenna configurations, and for different numbers of tags per object.

With unipolar tags we ran experiments comparing differently oriented pairs of tags. One orientation which we call *180-same* refers to two tags positioned on the same



(a) Comparison of multi-tags

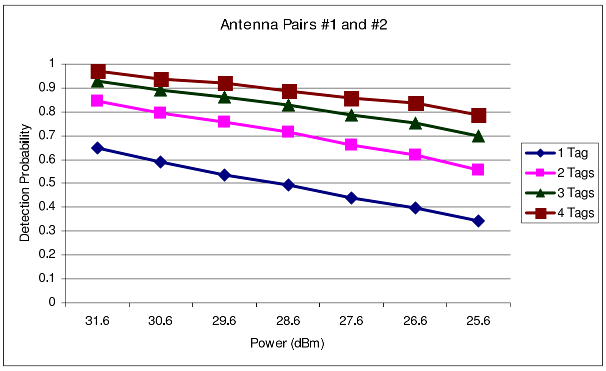


(b) Multi-tags versus multi-readers

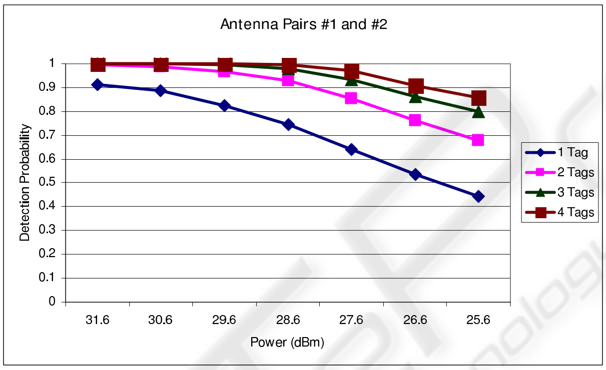
Fig. 5. Figure *(a)* shows the improvement in object detection probability for each object for *circular* antennas as the number of tags per object is increased. Figure *(b)* compares multi-tags with multiple readers for *circular* antennas. Attaching multiple tags to an object produces higher object detection probability than adding more readers.

plane and having identical orientation. The second orientation *180-diff* refers to two tags positioned on the same plane, but one of the tags is rotated 90 degrees relative to the orientation of the other tag. The third orientation *90-same* refers to two tags having identical orientation, but positioned on perpendicular planes. Finally, the forth tag orientation *90-diff* refers to two tags positioned on perpendicular planes with one tag rotated 90 degrees relative to the other tag. In our experiments we compared these four different tag orientations, and the results are presented in Figure 7(a). The results show that tags perpendicular to each other yield a higher probability of detecting at least one of them than tags that have identical orientation. In addition, to increase detection probability, it is better to position tags on perpendicular planes, rather than to locate all the tags in the same plane.

With bipolar tags we compared two possible tag orientations - 180, where tags are positioned on parallel planes, and 90, where tags are positioned on perpendicular planes.



(a) Two *linear* antenna pairs



(b) Two *circular* antenna pairs

Fig. 6. The two graphs show the detection probability for *linear* and *circular* antennas as a function of reader power for different numbers of tags per object. Observe that the detection probability decreases at a faster rate for circular than for linear antennas, as expected.

These are the only possibilities since tag orientations within the plane have no effect on bipolar tag detection. The results of the experiments shown in Figure 7(b) demonstrate no difference between tag orientations for omni-directional/circular antennas, but a drastic advantage for perpendicular 90 tags over parallel 180 tags for directional/linear antennas. These results show that multi-tags improve object detection not only because they increase the total antenna size per object and decrease the probability of antenna occlusions, but also because the expected grazing angle between the signal from the reader and one of the tags increases, which in turn raises the expected power on-board one of the tags. These findings confirm our theoretical expectations.

6 Controlling the Variables

It is important in RF experiments to carefully isolate and control the variables in order to ensure the accuracy of the results. Specifically, we controlled the effects of radio noise, reader variability, tag variability, the number and type of reader antennas, reader power

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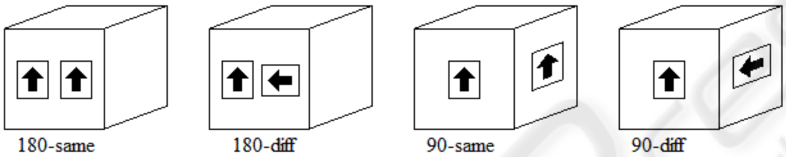
	Circular		Linear	
	1 Tag	2 Tags	1 Tag	2 Tags
180-same	0.4784	0.5500	0.3311	0.3700
180-diff		0.7454		0.5272
90-same		0.6727		0.5272
90-diff		0.8000		0.6363

(a) *Uni*polar tag orientation comparison.

	Circular			Linear		
	1 Tag	2 Tags	3 Tags	1 Tag	2 Tags	3 Tags
180	0.75	1	1	0.53	0.57	0.70
90		0.93	1		0.97	1

(b) *Bi*polar tag orientation comparison.



(c) Unipolar tag orientations.

Fig. 7. The two tables comparing object detection probabilities for *unipolar* and *bipolar* tags for different multi-tag orientations. The results show the significance of perpendicular multi-tag orientation, especially for directional/linear antennas. In Figure 7(a), *180-same* refers to identically oriented tags positioned on parallel planes; *180-diff* refers to perpendicularly oriented tags positioned on parallel planes; *90-same* refers to identically oriented tags positioned on perpendicular planes; *90-diff* refers to perpendicularly oriented tags positioned on perpendicular planes. In Figure 7(b), 180 refers to tags positioned on parallel planes; 90 refers to tags positioned on perpendicular planes.

level, and the distance from the reader antennas to the objects. To control the effect of ambient radio noise, we ran our experiments multiple times, sometimes even across multiple days to ensure that statistical properties of the data are stable. To accurately calculate improvements in object detection with multi-tags, we allowed sufficient time for the reader to read the tags. The reader parameters were carefully selected to ensure that all tags within a reader's detectability range are read. To ensure that our results are independent of the particular reader and antenna manufacturer/brand, we ran our experiments with readers and antennas from two different manufacturers. In all of our experiments we used consistent tag types and ensured that tag variability does not affect our experiments. We will discuss tag variability further below. The reader and identical reader antennas were carefully selected and objects were placed on a rotating platform at a fixed distance from the reader. The reader power levels were carefully controlled via a parameter in the software driver.

6.1 Tag Variability

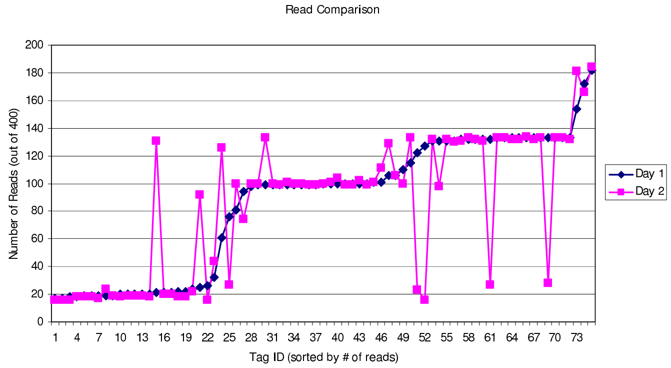
To determine tag properties and control tag variability we performed multiple tag variability tests. RFID tags with different chip manufacturers and antenna geometries have different detectability/receptivity properties [15]. The importance of tag receptivity and its use as a tag performance metric is addressed in [16]. Similarly, no two chips are truly identical due to inherent VLSI manufacturing variations [17]. Indeed, we found differences in tag detectability among tags of the same type, even among ones coming from the very same tag roll. In fact, these inherent tag receptivity differences were surprisingly high, with up to an order-of-magnitude difference in detectability between the "best" and "worst" tags. These findings provide yet another incentive for deploying multi-tags in order to ensure consistent object detection.

In our tag variability experiments, we used a ThingMagic reader, one circular ThingMagic antenna, and "UPM Rafsec UHF tag Impinj 34x54 ETSI/FCC" tags. Tags were elevated 26 inches from the floor, and positioned perpendicular to the antenna at a distance of 59.5 inches from the antenna center. The reader power level was set to $31.6dBm$. Each tag was read 200 times and the number of successful reads was recorded. We paused for 50ms between reads to allow tags sufficient time to lose power and initialize their state. The reader was allotted 10ms to read a tag. In this way, we computed the detectability/receptivity of 75 seemingly identical tags. To ensure data consistency, each experiment was performed twice and repeated the next day with the tags rotated 180 degrees.

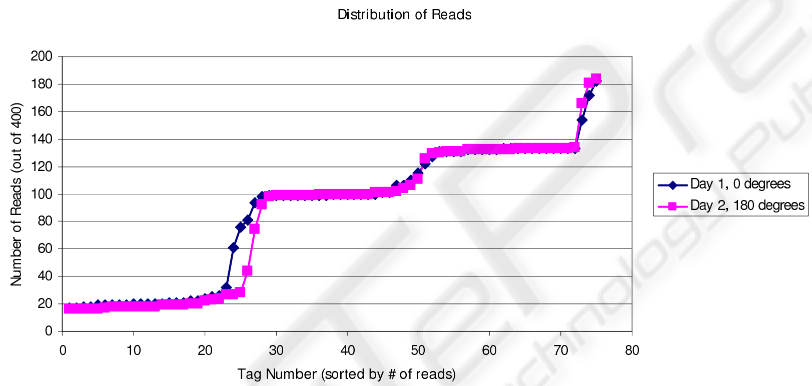
The smallest number of successful reads out of 200 was 8 and the largest was 91. The average was 43.44 and the standard deviation was 23.92. The Pearson product-moment correlation coefficient between two reads of each tag on the same day was 0.99 and the correlation between reads across two days was 0.98. Figure 8(b) shows the distribution of the number of successful tag reads. Figure 8(a) compares the number of successful reads for each tag across the two sets of experiments conducted on consecutive days, and Figure 8(c) depicts how the number of successful reads varies across different days. To magnify the visual spread between tags, we show the number of successful tag reads out of 400 by summing the detectability across the two runs of each day. Similarly high tag detectability variations were found in other UPM Rafsec tag types.

6.2 Reader Variability

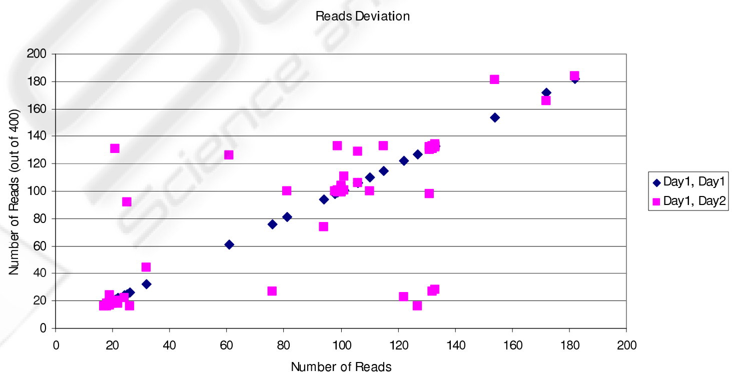
To ensure that our results are not dependent on the reader/antenna manufacturers, we repeated our experiments using ThingMagic readers and ThingMagic circular antennas. Since the tag detection algorithms used by ThingMagic and their implementations are different from those of Alien Technology, and since ThingMagic antennas are much bigger than those by Alien Technology, the detection probabilities we obtained differed between these two systems. However, the percentage improvements of multi-tags versus single-tagged objects were similar for both systems, supporting our hypothesis that the percentage improvements in object detection using multi-tags is mostly independent from the specific equipment used. Figure 9 shows the statistics of object detection improvements using circular ThingMagic antennas for a different number of tag ensembles per object. Note that the ThingMagic equipment enabled the collection of data for 3 and 4 antennas, whereas the Alien Technology readers work with only 1 and 2 antennas.



(a) Comparison of the number of successful reads per tag across two days. The tags are sorted based on the number of successful reads to better illustrate the data.



(b) This graph shows the distribution of successful tag reads across two days and two tag orientations. The number of successful reads shown is out of a total of 400 attempted. We observe a significant separation between several "clusters" of tag performance levels.



(c) This graph shows how the number of successful tag reads on the second day deviates from the number of successful reads on the first day.

Fig. 8. Characterizing tag detectability/receptivity by comparing the number of successful tag reads, the distribution of these reads, and the deviation in the number of reads across multiple experiments.

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	1 Antenna				2 Antennas			
	1 Tag	2 Tags	3 Tags	4 Tags	1 Tag	2 Tags	3 Tags	4 Tags
Power: 31.6 dBm	0.6528	0.8511	0.9291	0.9662	0.8335	0.9580	0.9874	0.9979
Power: 30.6 dBm	0.5668	0.7775	0.8761	0.9257	0.7567	0.9129	0.9537	0.9667
Power: 29.6 dBm	0.4813	0.6932	0.8033	0.8653	0.6755	0.8630	0.9233	0.9485
Power: 28.6 dBm	0.3818	0.5778	0.6960	0.7736	0.5614	0.7702	0.8588	0.9105
	3 Antennas				4 Antennas			
	1 Tag	2 Tags	3 Tags	4 Tags	1 Tag	2 Tags	3 Tags	4 Tags
Power: 31.6 dBm	0.8847	0.9782	0.9958	1	0.8910	0.9800	0.9970	1
Power: 30.6 dBm	0.8176	0.9442	0.9686	0.9750	0.8255	0.9465	0.9690	0.9750
Power: 29.6 dBm	0.7476	0.9100	0.9492	0.9615	0.7600	0.9160	0.9515	0.9630
Power: 28.6 dBm	0.6355	0.8323	0.9025	0.9400	0.6535	0.8450	0.9100	0.9445

Fig. 9. The detection probability statistics for *circular ThingMagic* antennas as a function of the power level for different antenna configurations and for a different number of tags per object.

7 Effects of Multi-tags on Anti-collision Algorithms

Anti-Collision algorithms allow a reader to uniquely identify tags while minimizing the number of tag broadcasting collisions (i.e., simultaneous interfering transmissions by the tags). Multi-tags have no effect on two variants of Binary Tree-Walking [1] [18], and may at most double/triple the total read time for dual/triple-tags over single tags for Slotted Aloha [1] and for Randomized Tree-Walking [19] [20] [21]. Our current experimental study of multi-tags addressed how multi-tags improve object detection. It is worth noting, however, that since not all tags are detected, the time required to identify all reader-visible tags is considerably less than double (or triple) the time needed to identify single-tagged objects.

In particular, from our experiments we observed that 25% to 65% of all tags are detected with one reader antenna, depending on its type and power level. Therefore, attaching two tags to each object may not add any significant overall time delay for object identification. In addition, current RFID technology can read hundreds of tags per second, making the increase in the number of tags insignificant, even for real-time systems. Moreover, in many scenarios the benefits of successfully identifying all the objects certainly justifies a modest increase in identification time.

8 Object Detection in Presence of Metals and Liquids

So far, our discussion of multi-tags has been restricted to scenarios where the objects to be identified contained no metal or liquid materials. In practical scenarios however, sets of items to be identified can contain mixtures of non-metallic objects, as well as partly metallic and liquid objects, making reliable object identification more problematic. It is more difficult to detect metals and liquids because they tend to interfere with radio signals, thus preventing readers from receiving accurately decodable tag responses. Metallic and liquid objects can also occlude other non-metallic objects, and thus interfere with the detection of these as well.

To detect metallic and liquid objects in our experiments, we had to considerably reduce the distance from the objects to the readers and to operate readers at high power levels. Based on our experimental results, multi-tags are highly effective in improving object detection in the presence of metallics and liquids. We observed an almost linear improvement in metallic and liquid object detection when the number of tags per object is increased, as compared to the rapidly increasing and then leveling curve for solid non-metallic objects. In addition, when metals and liquids are present, the detection probability curve for solid and non-metallic objects drops considerably, due to the radio interference created by the metallics and liquids. A more detailed treatment of the effects of multi-tags on metallic and liquid object detection will be reported elsewhere.

9 Economics of Multi-tags

Based on the results presented in this paper, we see that object detection probabilities are far from perfect even when multiple antennas and readers are used. Multi-tags, potentially in conjunction with multiple readers, can provide a viable solution to this problem. The cost of RFID tags in 2007 is around 10-20 U.S. cents a piece, making multi-tagging of high cost items viable even now. In addition, the cost of tags is dropping at an exponential rate following Moore's law, allowing for the cost-effective tagging of even low-cost objects in the near future. Also, RFID tags decrease in cost at a substantially faster rate than RFID readers, due to the economy-of-scale and improved yield trends inherent in their manufacturing; moreover, this price gap is expected to continue to widen. The future omnipresence and ubiquity of RFID tags is expected to eventually bring down the cost of RFID tags into the sub-penny level.

Many RFID tag types are delivered to the customer on a continuous paper roll, and the customer later programs the tags with unique IDs. We envision that tags will soon be cheap enough to embed into adhesive packaging tape that wraps around packages/containers, thus simplifying the multi-tagging of boxed objects and enabling automatic tag diversity and orientation selection to greatly improve object detection at negligible cost. Also, with higher tag ubiquity and the multi-tagging of objects, the testing of RFID tags will not be required as tag production yields become almost irrelevant, thus further reducing the cost of tag manufacturing and ensuring high object detection probabilities as well as improved dependability and reliability of RFID systems. In short, multi-tags are absolutely economically viable, and these benefits are bound to become even more dramatic over time.

10 Conclusion

Our experiments indicate that multi-tags are highly effective in improving object detection probability, yielding double-digit improvements over traditional single-tagged object RFID systems using both linear and circular antennas. Moreover, multi-tags can offer significantly larger improvements in object detection as compared to adding extra readers, even in the presence of objects containing metals and liquids, without exacerbating the burden on anti-collision algorithms. Multi-tagging of some objects is economically viable today, and as the cost of tags decreases rapidly, a wider range of applications will become possible with each year. We conclude that multi-tags can be an effective, and economically viable solution for RFID applications that require higher object detection probabilities.

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