Multi-Tag RFID Systems

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Abstract:
Successful object identification is the primary objective of radio frequency identification (RFID) technology. Yet, a recent major study by Wal-Mart has shown that object detection probability can be as low as 66%. We propose the tagging of objects with multiple tags to address the fundamental issue of object detectability. We show that this strategy dramatically improves the efficacy of RFID systems, even in the face of radio noise and other interfering factors. We define different types of multi-tag systems and examine their benefits using analytics, simulations, and experiments with commercial RFID equipment. We investigate the effect of multi-tags on anti-collision algorithms, and develop several techniques that enable multi-tags to enhance RFID security. We suggest new promising applications of multi-tags, ranging from improving patient safety to preventing illegal deforestation. We analyze the economics of multi-tag RFID systems and argue that the benefits of multi-tags will continue to increasingly outweigh their costs in many applications.

Keywords: RFID, reliability, multi-tags, tag detection, tag receptivity

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Biographical notes:
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1 Introduction

A typical RFID system consists of readers (sometimes called beacons), tags (sometimes called transponders), and back-end servers that receive and process the information that the readers collect from the tags [5] [15] [17] [19] [20] [25] [28] [38] [45] [47]. There are three types of RFID tags: active, passive, and semi-passive. Active tags have batteries on-board and can initiate transmission on their own. Passive and semi-passive tags rely on power from a reader to engage in communication. Semi-passive tags have batteries on-board, but they are only used for on-board computations. There are two coupling mechanisms used by passive and semi-passive tags: inductive coupling and electromagnetic backscattering (or 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.

In many applications tags are passive in order to extend their useful lifetime and to reduce the overall cost of an RFID system. The largest anticipated RFID deployment is the replacement of bar codes with RFID tags. For this deployment to be realized, the cost of an RFID tag must decrease substantially, into the low pennies range. Also, tag detection issues as well as privacy and security concerns need to be resolved in order to avoid commercial loses, and to preempt the boycotting of RFID technology by privacy advocacy groups [1] [2]. We expect the work described here to help hasten the realization of full-scale commercial deployments of RFID technology.

1.1 The Motivation for Multi-Tags

Bar code scanners require a line-of-sight to the bar codes, and they usually have to be close to the objects being identified. Moreover, bar codes are scanned one at a time, and the bar code scanners (or the bar codes themselves) must physically move between successive reads. This mechanical process limits the read rate to at best only a few bar codes per second. On the other hand, RFID readers can read hundreds of tags per second without requiring line-of-sight, thus allowing the easy automation of the reading process and making RFID-based identification very appealing commercially. As the identification process is automated, however, we must ensure the successful reading of all the tags within the readers' field.

Object detection is impeded by ubiquitous background radio noise. Moreover, metals and liquids reflect and/or absorb radio signals, further degrading the readers' 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 with low profit margins 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 [22].

The report by the Defense Logistics Agency [46] showed that only 3% of the tags attached to objects moving through the Global Transportation Network (GTN) did not reach the destination (165 single-tagged objects were tracked in this study). However, the same report shows that only 20% of the tags were recorded in GTN at every checkpoint, and at one of the checkpoints fewer than 2% of tags of one particular type were detected. In addition, some of the tags were registered on arrival, but not on departure. As a result of these low object detection rates, accurate real-time tracking of objects moving through the GTN network was not possible. This report underscores the unreliability of object detection using a single RFID tag per object.

In addition to ambient radio noise, environmental conditions such as temperature and humidity can also adversely affect the success of object detection [18]. Moreover, objects moving at high speeds can have significantly reduced detection rates. The number of objects stacked together, variation in tag receptivity (even among tags from the same manufactured batch), and tag aging (and degradation in general) can diminish the detection probabilities as well. Also, objects tagged with a single tag are easier to steal (a simple metal foil placed over the tag can block detection). RFID systems used in healthcare pose a special dependability challenge, since RFID system deployment will directly affect patients' welfare.

To address the problems discussed above, we propose attaching multiple RFID tags to each object, as opposed to using only a single tag per object. Multi-tags will greatly improve object detection probabilities and increase reader-tag communication distances, even in the presence of metallics, liquids, radio noise, and adverse environmental conditions. Multi-tags will greatly benefit theft deterrence and prevention applications, as well as dependable computing applications such as healthcare, where higher reliability, availability, and safety are required. All these benefits can be achieved at reasonable cost, as we discuss below.

2 Definitions

We define four broad types of multi-tags:

I. *Redundant tags* - two or more independent tags carrying identical information and performing identical functions.

II. *Complementary Tags* - two or more disconnected tags that complement each other for a common purpose.

III. *Dual-Tags* - two tags connected to each other and having one or two antennas;

Type-IIIa - all memory is shared by the tags;

Type-IIIb - each tag has its own memory and no memory is shared;

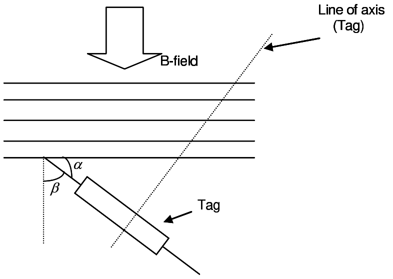
Type-IIIc - both tags have their own memory as well as shared memory;

IV. *N-Tags* - N tags connected to each other and having one or more antennas.

Note that type-IV subsumes type-III (where N=2), but for some application scenarios we may specifically wish to use exactly two tags per object, hence the special "dual-tags" category.

3 The Multi-Tag Approach

We base our analysis of multi-tags on the expected angle of incidence of the radio signal from the reader to the tag. We perform the analysis for inductive coupling as well as for far-field propagation. In the case of inductive coupling, Figure 1 depicts the angle α of the tag relative to the perpendicular direction of the signal transmitted from the reader, and gives the formula of the voltage induced in the tag by the received signal [29]. We analyze the expected voltage in one tag, as well as in ensembles of two, three, and four identical tags, assuming a fixed frequency, signal strength, and antenna geometry (i.e., loop area and number of coil turns). In other words, we focus on the parameter that induces many of the benefits of multi-tags, namely the expected incidence angle of the arriving signal.



$V_0 = 2\pi f N S B_0 \cos\alpha$

where:
f = frequency of the arrival signal
N = number of turns of coil in the loop
S = area in the loop in meters (m^2)
B_0 = strength of the arrival signal
α = angle of the arrival signal

Figure 1: Reader induced voltage on the tag

We define the angle β to be the angle between the tag and the direction of the arriving signal (rather than focusing on the angle between the tag and the perpendicular orientation of the tag to the B-field). We therefore replace $\cos(\alpha)$ with $\sin(\beta)$ in the voltage equation in Figure 1. Our goal is to maximize $\sin(\beta)$ in the voltage equation in order to maximize the induced voltage and thus the strength of the received signal.

Similarly, for far-field propagation, the voltage induced in the antenna by the signal is proportional to the gain of the antenna, which in turn is proportional to Poynting's vector $p = E \times H$ where E is the instantaneous electric field intensity and H is the instantaneous magnetic field intensity. We also have $E \sim \sin(\beta)$ and $H \sim \sin(\beta)$. Therefore, we obtain $voltage \sim \sin^2(\beta)$ [4] [15] [43]. So, for both inductive coupling and far-field propagation, we seek to bring the expected incidence angle β of the signal closer to 90 degrees.

The first question is how to orient the tags relative to each other in order to maximize the expected angle of incidence of the radio wave with respect to one of the tag 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). 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, we can position them perpendicular to one another in the x-y and x-z planes. Similarly, for three tags, we can position them pairwise perpendicularly in the x-y, x-z, and y-z planes. For four tags, it 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. See Figure 2 for a graphical representation of optimal multi-tag positioning.

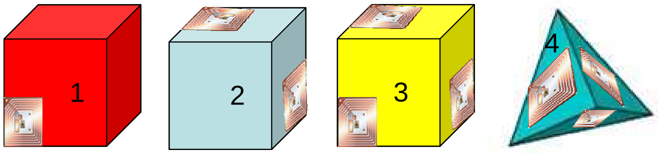


Figure 2: Optimal multi-tag positioning for ensembles of 1, 2, 3 and 4 tags.

The second question asks what is the actual expected maximum incidence angle of the arriving signal, for a given tag ensemble, with respect to the antenna of any of the tags. To answer this question, we computed the expected incidence angle analytically for one and two tags. We also developed a software simulator that computes the expected angle for an arbitrary number of tags. For a given tag configuration, our simulator calculates the average value of the maximum angle to any tag over many randomly generated simulated signals.

The results obtained from the analytical computations agree with the experimental results for one and two tags. This raises our confidence level in the correctness of the simulator's results for larger tag ensembles (i.e., three and four tags), which were computed only using the simulator, since the complex geometries involved make it intractable to analytically compute these quantities.

The expected incidence angle for one tag is:

$$\frac{\int_0^{\frac{\pi}{2}} x\,(2\pi\cos(x))\;dx}{2\pi} \approx 32.7\;(degrees)$$

The expected incidence angle for two tags is:

$$\frac{\int_0^{\frac{\pi}{4}} x\,(2\pi\cos(x))\;dx + \int_{\frac{\pi}{4}}^{\frac{\pi}{2}} \left(\frac{\pi}{2} - x\right)(2\pi\cos(x))\;dx}{\pi} \approx 48.0\,(deg)$$

These integrals determine the average incidence angle by slicing the upper hemisphere horizontally and using the circumference of each slice as an averaging coefficient.

To calculate the expected angle of incidence, our simulator generates a random uniformly distributed point on the surface of a sphere [31]. This determines the direction of a random uniformly-distributed radio signal relative to the origin, and calculates the angle to every tag in the multi-tag ensemble, while recording the largest of these angles. Our simulation generates 10 million such random trials and averages the induced maximum angles. Figure 3 shows the simulation results of the expected largest incidence angle for one, two, three and four tag configurations.

We note that there is a two digit increase in the expected 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 improvement as we move from three tags to four tags. This suggests that adding an extra tag or two may be beneficial for the purpose of increasing the induced voltage (and thus improving the communication range), but using four or more tags will not garner substantial additional benefit in that respect. Nevertheless, even though the benefit of having more than three tags per object in order to increase the reader-tag communication range may be relatively small, there are other benefits to using more than three tags. For example, if an alternate benefit of multi-tags (e.g. theft prevention) is the primary goal, we may still benefit from using more than three tags per object (and we can achieve further detection improvements by optimizing the tags' positioning). Figure 4 shows the absolute and relative voltage improvements for various multi-tag ensembles.

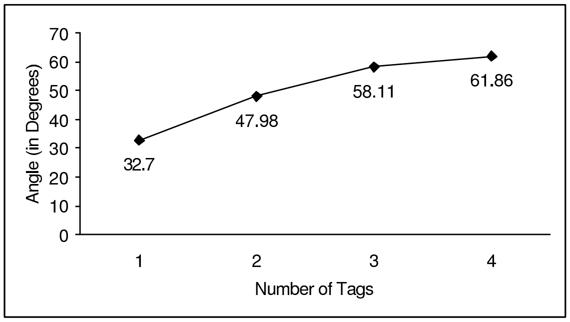


Figure 3: Expected largest incidence angle to any tag.

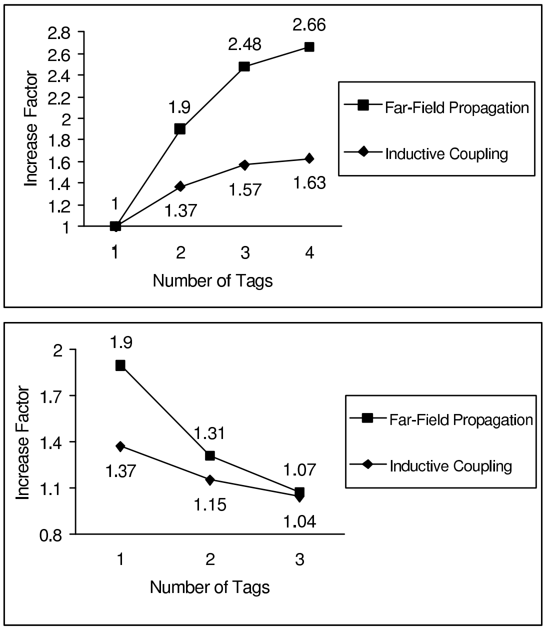


Figure 4: Absolute and relative induced voltage increase on the tags.

Our incidence angle -based analysis assumes that the signal can come from any direction with equal likelihood, which is realistic for many applications (e.g., goods randomly piled inside a shopping cart). However, for some applications where the position/orientation of the object is known in advance, or where it may only span a narrow range of possibilities, the optimal positioning of the tags may be different from the assumption-free ones suggested above. Similarly, the number of tags may vary among objects, to further optimize overall detection.

4 Experimental Equipment and Setup

To validate our analytical and simulation studies, we conducted an extensive experimental evaluation of multi-tags. Our experiments were performed using commercial FCC-compliant equipment, namely Ultra High Frequency (UHF) readers manufactured by Alien Technology (model ALR-9800, four antennas, multi-protocol, 915 MHz) and ThingMagic (model Mercury 4). We utilized 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 picked unipolar UPM Rafsec UHF "Impinj 34x54 ETSI/FCC" tags and bipolar UPM Rafsec UHF "Impinj 70x70 ETSI/FCC" tags for our experiments.

We performed the experiments in an otherwise empty room in order to minimize radio interference and signal reflection anomalies. We placed multiple tags on a diverse set of 20 solid non-metallic objects using four tags per object, and a set of 20 metal and liquid-containing objects using three tags per object. We positioned tags perpendicular to each other whenever possible, and spread the tags as far apart in space across an object as possible, in order to minimize tag occlusions by other tags and/or objects. The experiments with solid non-metallic objects used sets of both unipolar and bipolar tags. The experiments containing metallic and liquid objects were performed only with unipolar UPM Rafsec UHF "Impinj 34x54 ETSI/FCC" tags. We wrote two software drivers to communicate with the two types of readers. The driver for the Alien Technology system is based on Java API obtained from Alien Technology, whereas the driver for ThingMagic implements both the experiments' logic and the reader-computer communication protocol.

We positioned Alien Technology reader antennas side-by-side in pairs, with each pair consisting of a sending and a receiving antenna. Each pair of antennas was equidistant to the center of a plastic bag containing objects, placed 20.5 inches above the floor, and aligned perpendicularly towards the center of the bag. 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 were minimized. In a separate set of experiments, circular ThingMagic antennas were equidistant and perpendicular to the bag containing the objects, located 33 inches above the floor, in the rectangular "gate" formation. Each ThingMagic antenna was both sending and receiving signals. As with the Alien Technology hardware, we allowed sufficient reader time for object identification. We randomly (re)shuffled the tagged objects multiple times to change the tags' spatial 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 random 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 $\sqrt{\mathrm{power}}$.

5 Experimental Results

5.1 Linear Antennas

Our experiments show that multi-tags considerably improve object detection probabilities for linear antennas. Switching from 1 to 2 tags per object produces a high double-digit increase in object detection probability. Upgrading from 2 to 3 tags results in a low double-digit increase, but going from 3 to 4 tags gives only a single-digit increase in object detection. These results corroborate our theoretical expectations [7]. Figure 5(a) graphically shows the increase in object detection probability for each object (the objects are sorted along the X-axis according to their 1-tag detection probabilities). We observe significant separations between the first three curves. In Figure 5(b), we compare object detection improvements between two tags per object versus two reader antennas. From this data we observe a dramatic double-digit improvement resulting from adding a second tag to each object, but only a low single-digit improvement from adding a second reader. We can see almost a factor of 4 improvement in object detection probability when using multi-tags, as compared to using multi-readers.

5.2 Circular Antennas

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, we observed that for circular antennas the advantage of adding a tag is on par with that of adding a reader. We also saw that the average object detection probabilities decrease more rapidly for circular than for linear antennas, as a function of decreasing antenna power.

5.3 Object Detection in the Presence of Metals and Liquids

It is more difficult to detect metallics and liquids because they tend to interfere with and occlude 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. When metals and liquids are present, the detection probabilities for solid and non-metallic objects decrease due to radio interference from the metallics and liquids. We observed a 4 to 10 percent decrease in the detection probability of solid objects, depending on the antenna type and the number of tags per object, as compared to scenarios where no liquids or metallics are present [10].

To detect metallic and liquid objects in our experiments, we had to considerably reduce the distance from the objects to the readers to ensure that tags are actually detectable at that range. Specifically, we reduced the approximate reader-to-tag distance to 32 inches, from the 55 inch range used for solid and non-metallic objects. In addition, we had to operate the readers at high power levels only. 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 detection probability curve for solid non-metallic objects. Figure 6 shows the detection probability statistics for several power levels and antenna configurations.

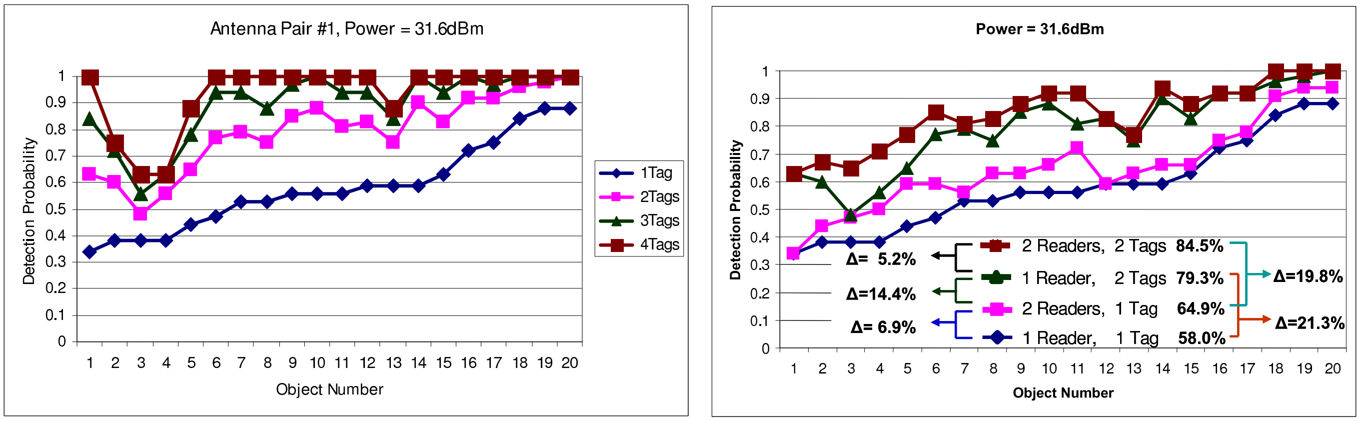
5.4 The Effect of Object Quantity on Object Detection

Aside from environmental conditions such as temperature and radio noise, and the presence of metallics and liquids in the objects' vicinity, the mere number of objects stacked together affects the average detection probability of an object. This occurs because the objects to be identified act as radio signal occluders, shielding other objects' tags from the readers. We performed two back-to-back experiments to determine the effect of the number of objects on the average object detection probability. In these experiments we used circular ThingMagic antennas and unipolar tags. In the first experiment, we grouped 15 solid non-metallic and 15 metallic and liquid objects and determined the average object detection probabilities for liquids and metallics, and separately for solid, non-metallic objects. In the second experiment, we grouped 20 solid non-metallic and 20 liquid metallic objects, and again determined the average object detection probabilities.

To ensure that the reader has sufficient time to detect all reader-visible tags in both experiments, we allocated 3 seconds for the reader to detect tags in the $15/15$ experiment and (proportionally) 4 seconds for the $20/20$ experiment. The detection probability statistics were calculated for various numbers of tags per object, as well as different numbers of reader antennas. For accurate comparison, in calculating the statistics in the second experiment we used a subset of 15 solid non-metallic and 15 liquid metallic objects that matched the objects in the first experiment.

We compared the average object detection probabilities between the two experiments, varying the number of tags per object and the number of reader antennas. Figure 7 shows the results of this comparison for metallic and liquid objects. The average detection probability of an object in a $15/15$ experiment is greater than in a $20/20$ experiment, as expected (since higher numbers of objects increase the likelihood of occlusions). The difference is more dramatic for metallic and liquid objects than for solid non-metallic ones because the reader is operating at a high power level in order to detect metallic and liquid objects.

Note that the difference in object detection probabilities between the two experiments is greater when more tags are attached to an object, and when multiple readers are used for object identification. This occurs due to an overall improvement in object detection when multi-tags and multiple readers are used. These experiments clearly illustrate that multi-tags have a more positive influence than multiple readers on detection probabilities, especially in the presence of metallics and liquids, and when identifying larger groups of objects.



(a) Comparison of multi-tags

(b) Multi-tags versus multi-readers

Figure 5: (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.

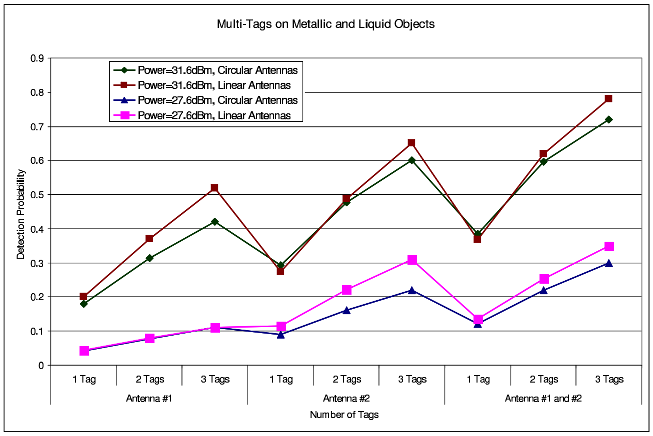


Figure 6: Comparison of average detection probabilities of metallic and liquid objects using one and two linear and circular antennas for various power levels.

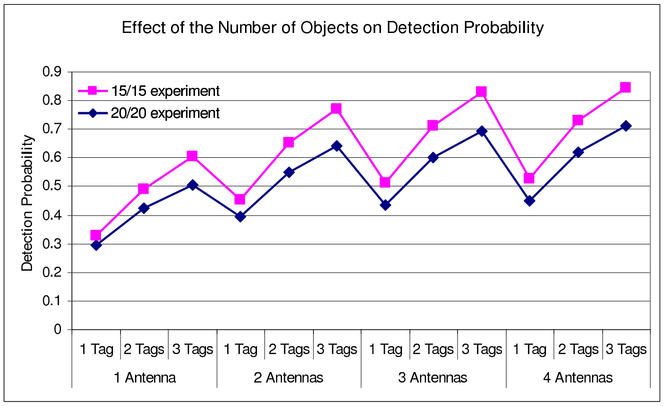


Figure 7: The effect of the number of objects on the average object detection probability. In the *15/15 experiment* we used 15 metallic and liquid objects, and 15 solid non-metallic objects. Similarly, in the *20/20 experiment*, we used 20 metallic and liquid objects, and 20 solid non-metallic objects.

5.5 Importance of Tag Orientation

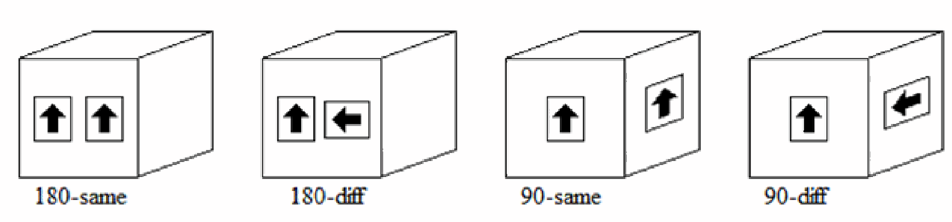
One of the major conclusions of our theoretical analysis of multi-tags [7] is that tags need to be oriented perpendicular to each other to obtain the most benefits in object detection. We experimentally confirmed this observation by varying the tag orientation, collecting tag identification data, and calculating object detection probabilities for different multi-tag orientations. In [6] 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.

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 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 8. The results show that tags perpendicular to each other yield a higher probability that at least one of them will be detected than tags that have an identical orientation. In addition, to increase the 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. These are the only possibilities, since tag orientations within the plane have no effect on bipolar tag detection. The results of the experiments demonstrate no difference between tag orientations for omnidirectional/circular antennas, but a drastic advantage for per-

	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.



(b) Unipolar tag orientations.

Figure 8: The comparison of object detection probabilities for *unipolar* tags for different multi-tag orientations. The results show the significance of perpendicular multi-tag orientation, especially for directional/linear antennas. In Figure 8(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.

pendicular 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 experimental 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 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 the statistical stability of the data. 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 (to easily vary their angle) 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 the intrinsic tag characteristics and control tag variability we performed multiple tag variability tests. RFID tags with different chip manufacturers and antenna geometries have different detectability/receptivity properties [44]. The importance of tag receptivity and its use as a tag performance metric is addressed in [23]. Similarly, no two chips are truly identical due to inherent VLSI manufacturing variations [13]. Indeed, we found differences in tag detectability among tags of the same type, even among ones coming from the very same tag roll (i.e., manufactured batch). 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" supposedly identical tags. These findings provide yet another incentive for deploying multi-tags in order to ensure consistent object detection.

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 employed by Alien Technology, and since ThingMagic antennas are much bigger than the Alien Technology ones, the detection probabilities we obtained indeed 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 of the specific equipment used.

7 Effect of Multi-Tags on Anti-Collision Algorithms

Anti-Collision algorithms enable 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 [15] [27], and may at most double/triple the total read time for dual/triple-tags over single tags for Slotted Aloha [15] and for Randomized Tree-Walking [8] [12] [50]. Our theoretical and 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 by some anti-collision protocols.

In particular, from our experiments we observed that 25% to 75% of all tags on solid/non-metallic objects are detected with one reader antenna, depending on its type and power level. The percentages are much lower for metallic and liquid objects. Therefore, attaching two tags to each object may not add any significant overall time delay for object identification. Moreover, current RFID technology can read hundreds of tags per second, making the increase in the number of tags insignificant, even in real-time systems. Finally, in many scenarios the benefits of successfully identifying all the objects certainly justifies a modest increase in identification time. Based on the above observations, RFID system designers should select an appropriate anti-collision algorithm based on the number of objects that may have to be identified near-simultaneously, the number of tags attached to each object, and the expected objects' velocities (if the objects to be identified are moving).

8 Multi-Tags as Security Enhancers

8.1 Chaffing and Winnowing

Multi-tags can provide enhanced security using the idea of "chaffing and winnowing" [40]. Chaffing creates messages with phony message authentication codes (MACs), and winnowing filters fake messages by comparing the MAC received along with the message against the MAC computed by the recipient. The achieved confidentiality can be made arbitrarily strong with smaller packet sizes. Sending chaff probabilistically, or controlling the amount of chaff sent will hide the real number of tags in the reader's interrogation zone [50].

8.2 Preventing Side-Channel Attacks

Multi-tags can prevent certain side-channel attacks. For example, multi-tags help prevent a "power analysis" that an adversary can deploy against EPC tags in order to learn the kill password, as demonstrated by Oren and Shamir [36]. They showed that when an EPC compliant tag receives a kill password one bit at a time, its power operation changes, allowing an adversary to detect power spikes when an invalid bit is received. In a multi-tag scenario, one tag can counter-balance the power budget of the other tag by operating in an "opposite" mode, thus preventing simple power analysis, and consequently preventing the discovery of a kill password by an adversary.

8.3 Splitting ID Among Multi-Tags

In a set of multi-tags, the tag ID/data can be split among several individual tags, and the tags can transmit data at different frequencies using Code-Division Multiple Access (CDMA), making it difficult for an adversary to reconstruct the complete signal. This technique was used by the British during World War II to prevent the Germans from jamming Allied transmissions [34].

9 Applications of Multi-Tags

Multi-tags can be deployed in a variety of useful applications and serve many purposes. They can be used for specific tasks such as determining the location and orientation of objects, as well as ensuring system reliability, availability, and even safety. In addition, multi-tags can be a considerable deterrent to illegal activities such as theft and forgery, and they can enhance RFID security and privacy. For example, multi-tags can speed up the execution of some algorithms through parallel computation. Below, we give examples of scenarios and systems where multi-tags can be effective. These examples do not cover all possible applications; rather, they serve mainly to illustrate the wide range of uses and applications of multi-tags.

9.1 Reliability

There are many RFID applications where system reliability is critical. For example, in a store scenario, checkout RFID readers should reliably detect all items purchased by the consumer. Missed items, even at a relatively low rate of 1%, can incur huge losses to a typical low-profit-margin business, thus significantly affecting the store's bottom line. Also, objects moving through a supply chain should be detected reliably to enable accurate real-time inventory control and early theft detection. In general, in most applications where goods change hands or objects move through an RFID checkpoint, all objects should be detected and identified accurately. Multi-tags attached to objects will greatly increase objects' detection probabilities at a reasonable cost.

9.2 Availability

One example where multi-tags can improve system availability is in "yoking-proof" scenarios, where a potentially adversarial reader communicates with a group of tags and generates a proof that the tags were identified near-simultaneously [9] [26]. The constructed proof is later verified by an off-line verifier. The integrity of the system hinges on the tags of *all* objects being detectable by the reader when required, since otherwise no valid proof can be created, even by an honest reader. The problem is exacerbated because of the tight timing constraints of the protocol, and the inherent variations in tag receptivity [6]. In such "yoking-proof" scenarios, multi-tags can be attached to each object, thus greatly increasing the probability of at least one tag per object being detectable. Note that here multi-tags may need to be physically connected to each other, so that they can consistently share their states with each other in order to prevent the possible forgery of a yoking proof (or else the tags must have distinct keys and the reader selects one detectable tag per object as a "leader" for that object).

Applications of yoking-proofs include verification by auditing bodies that a bottle of medicine was sold together with its usage instructions leaflet, or that safety caps were sold/delivered together with the associated devices, etc. Such scenarios can directly improve consumer safety by using multi-tags to ensure that a set of related objects is detected near-simultaneously. Another example of an application where availability is important is the real-time tracking of critical household or business objects such as remote controls, car keys, firearms, and important documents, among others.

9.3 Safety

Another, perhaps unexpected, area where multi-tags can be of great benefit is safety. Specifically, multi-tags can be used in healthcare to track medical instruments (e.g., gauze sponges). For example, surgical sponges, among other foreign objects, are sometimes left inside humans during operations, causing highly undesirable consequences that adversely affect the patients. Recent medical studies [30] have shown surprisingly good results in detecting RFID equipped surgical gauze sponges during operations. However, to accurately detect *all* the sponges requires very careful and precise positionings of the reader. If the distance between the reader and the tags is increased even slightly, the tags may go undetected and thus the object may be inadvertently left inside the patient. In addition, the sponges may be located amid bodily liquids, further decreasing the detection probabilities. Finally, the tags on the sponges may break or malfunction, causing readers to miss tags, which may result in serious human injury. Attaching multi-tags to surgical sponges will greatly increase the probability of all sponges being detected and accounted for, which would translate into improved patient safety and reduced liability.

Surgeons who participated in the study [30] estimated that the cost of RFID technology to detect sponges is about $\$144$ per patient. We believe that this cost can be substantially reduced, especially since such expenses can be amortized across many hospitals, operations, and patients. In addition, the cost of the RFID equipment deployed to ensure patient safety in hospitals may be viewed as part of the hospitals' insurance against malpractice lawsuits, and therefore this cost can be factored into the overall cost of a medical procedure or operation. Overall, we believe that investment in multi-tag RFID systems for safety-critical applications is highly cost-benefit justifiable. We discuss the economics of multi-tag RFID systems in greater detail in Section 10.

9.4 Object Location

The location of a *multi-tagged* object can be more accurately determined than that of a *single-tagged* one. Well known location triangulation methods can be utilized to determine the position of each tag, thus reducing the error in computing a multi-tagged object's location coordinates. A carefully engineered multi-tag RFID system can be used to determine not only an object's position, but also its spatial orientation [21]. Directional antennas and orientation-sensitive RFID tags can be deployed to make such a system highly effective. Creating a working prototype of such a system and applying it in real-world scenarios is an interesting area for future research.

9.5 Packaging

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, e.g., adhesive packaging tape used to wrap packages and 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. With higher tag ubiquity and the multi-tagging of objects, the testing of RFID tags will be obviated, since even a low tag production yield will enable the overall system to function properly. The acceptability of lower tag manufacturing yields will further reduce the production costs, while ensuring high object detection probabilities as well as improved dependability and reliability of RFID systems.

9.6 Security

Multi-tags can be used to speed up the execution of private-key privacy-preserving authentication algorithms [8] [32], as well as provide a physical mechanism for resisting tag cloning [11]. In such algorithms, secret keys are assigned to the edges of a tree and tags correspond to tree leaves. The reader knows the secrets of the entire tree. The reader and a tag can authenticate each other by running a secure authentication algorithm for each edge of the tree of secrets, following a path from the root to the leaf where a tag is located. The secure authentication algorithm is keyed with the secret corresponding to the tree edge along the path. By arranging the tags at the leaves of the tree, the tag identification time is reduced from $O(n)$ to $O(log(n))$ where n is the total number of tags in the system. With multi-tags, such reader-tag authentication algorithms can run in parallel on different branches of a single tree level, as well as run predictively / speculatively at lower tree levels.

9.7 Theft Prevention

Another useful set of applications of multi-tags is in theft prevention. Increasing the number of tags attached to (or embedded in) an object will make it much more difficult for a thief to shield or remove all of the tags, thereby increasing the probability of him getting caught. For example, one intriguing application of this could be the prevention of illegal deforestation by embedding tags in the trunks of living trees [7]. Since tags are very cheap compared to the cost of lumber (especially for rare or legally-protected trees such as Redwoods), the economics of such applications are financially viable. When logs are shipped and sold, they can be scanned for tags whose presence will determine the origin of the wood (and possibly convey other useful information, such as weather and environmental statistics tracked over the tree's lifetime). It would be prohibitively expensive for illegal loggers to detect and remove all of the tags from a given tree trunk, thus substantially increasing the cost and risk of illegal deforestation, at a relatively low cost to the protection agencies.

DataDot Technology USA, Inc [14], produces "polyester substrate micro-dots" with laser etched identification data. These micro-dots can be applied to a surface, thereby marking it with unique identifiers that can later be read optically. A consumer applies micro-dots to his valuables and registers these micro-dots with DataDot Inc., which makes the information available to law enforcement agencies. DataDot Technology reports that this technology has greatly reduced the theft of marked items, and facilitated the recovery and return of stolen valuables [14]. We envision that RFID tags will eventually become cheap enough to enable the sprinkling of multi-tags onto objects, as with "micro-dots", thus providing ubiquitous and permanent wireless identification capability. A thief can not realistically hope to reliably find and/or shield *all* of the numerous RFID tags thus sprinkled on an object (e.g., throughout a car). In addition, the attempted shielding of large collections of multi-tags can itself indicate a probable illegal intent.

The attachment of the radio antenna(s) to the silicon chip, and tag packaging itself incur the majority of the cost in RFID tag manufacturing [37]. However, if we use multi-tags for theft prevention as described above, we do not need to package the tags, nor be particularly precise or careful when attaching antenna(s) to chips. The mere large number of tags per object will guarantee that enough tags are still detectable, and will thus deter theft. The simpler process of producing unpackaged tags will considerably streamline the tag manufacturing process and consequently reduce their cost. In addition, in such scenarios, manufacturing yields are no longer required to remain high, and tag testing may be skipped as well, further contributing to significant tag cost reductions. We discuss the economics of multi-tag RFID in more detail in the next section.

9.8 Tagging Bulk Materials

Cheap redundant multi-tags can be embedded into bulk materials (e.g., fertilizers, explosives, chemicals, propellants, crude oil, etc.) to prevent their unintended acquisition, transportation, and possible misuse. If tags are embedded into certain bulk materials at a reasonably small proportion to the size/quantity/weight of a substance, they will not adversely affect the normal use of these materials (e.g., crude oil can be tagged at the rate of 10 multi-tags per barrel, and these tags can be removed during the final stages of the refinement process). If required, the tags can have limited lifespans or even be (bio)degradable. The RFID tagging of fertilizers / explosives can help law enforcement agencies trace the producer and/or buyer. The tagging of bulk materials can also directly *prevent* criminals / terrorists from causing damage by enabling law enforcement agencies to detect the presence of dangerous substances in proximity (or ominously en route) to sensitive locations or particular sites of interest, hopefully *before* an illegal act transpires.

10 The Economics of Multi-Tags

Based on our object detection experiments [6], it is clear that object detection probabilities are far from perfect, even when multiple readers / antennas are used. Multi-tags, potentially in conjunction with multiple readers, can help address this problem. The cost of RFID tags in 2007 is around 10 U.S. cents each, making the multi-tagging of high-cost items currently viable. In addition, the cost of tags is decreasing at an exponential rate following Moore's law, and this trend will enable the cost-effective tagging of even low-cost objects in the near future. Also, the cost of RFID tags is decreasing substantially faster than the cost of RFID readers, due to improving manufacturing yields and an economy-of-scale driven by massive deployments. Moreover, this price gap is expected to continue to widen due to the increasing demand for cheap RFID tags. The anticipated future omnipresence and ubiquity of RFID tags is expected to eventually reduce the cost of RFID tags into the sub-penny level.

10.1 The Costs and Benefits of Multi-Tags

The cost of passive RFID tags has been decreasing rapidly over the last decade. From 2001 to 2006 the cost of passive tags has steadily dropped from $1.15 to $0.08 a piece, when at least 1 million units were purchased [33] [35] [41]. Based on this historical data, we predict that tags will cost $0.06 by the end of 2007, and 5 cents in 2008. A 5 cent price point for tags was considered the threshold for supporting a strong business case for item-level tagging [42], and now this target price is just around the corner. Based on the efforts of some companies and researchers working on RFID tag technology [37], we believe that ~ 1 penny tags will become a reality around the year 2011. Eventually, tags will be printed directly onto objects and cost less than a penny to produce. This cost milestone will make RFID a truly ubiquitous and affordable technology. Figure 9 depicts the historical (and our projected) decreasing cost trends for tags.

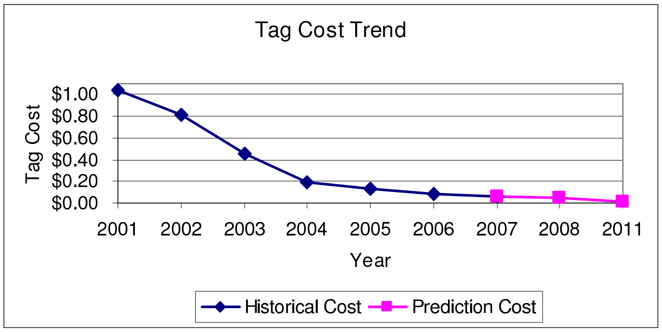


Figure 9: The decreasing cost trend of passive RFID tags over time, and our cost prediction for the future. The price per tag is based on the purchase of 1 million lots.

When considering the cost of RFID tags or even the cost of an entire RFID system, it is critical to also analyze the benefits that RFID brings to an application. A complete business analysis of deploying RFID should be performed, since the benefit of deploying RFID in an application can considerably outweigh the cost, even at today's prices. Specifically, the business analyses of RFID systems should take into account the direct savings that RFID deployment will enable, such as higher employee productivity, automated business processes, workforce reductions, and the valuable information collected through RFID.

In supply chain management scenarios the benefits of RFID deployment are tremendous. First, the merchandise can be tracked in real-time, allowing more efficient scheduling of operations. RFID may also allow reductions in the number of workers, since many currently manual processes can be automated. RFID can also prevent theft of goods, which are stolen predominantly by insiders. According to [16] [49], insider thieves outnumber outsider thieves six to one. It has been documented that over 1% of goods in retail stores are stolen [49], and the real losses due to theft are likely to be much higher, as companies tend to underreport theft statistics. Multi-tag technology enables objects to be tracked more effectively, not only during transport or check-out, but also during manufacturing and warehousing, which can significantly reduce theft rates and thereby increase profits.

10.2 Tag Manufacturing Yield Issues

Manufacturing yield is one of the main criteria that influence the cost of VLSI chips. This is because customers have to pay not only for the good chips delivered to them, but also for the defective chips that never made it out of the fabrication facility, as well as for the labor-intensive separation of the good ones from the defective ones. For example, according to recent research by RFID vendors, as many as 30% of RFID chips are damaged during production when chips are attached to their antennas, and an additional 10 to 15 percent are damaged during the printing process [18].

Due to the redundancy built into our proposed multi-tag RFID systems, we can often ignore the manufacturing yield. Some manufactured RFID tags may be defective, while others may fail in the field, but if multiple tags are attached to each object, the probability that all the tags fail is still quite small. This considerably increases the overall reliability of a multi-tag RFID system, and also decreases the tag manufacturing costs (e.g., expensive manufacturing steps such as testing may be dispensed with).

The failure rate of deployed RFID tags in the field is estimated to be as high as 20% [39]. This large failure rate induces an additional cost pressure on RFID tag manufacturing, since individual tags must be made more reliable, and/or extensively tested after manufacturing. Even after packaging, tags may become defective. For example, 5% of the tags that we purchased for our experiments were marked by the manufacturer as defective; moreover, we discovered several additional inoperable tags during the tag programming phase of our experiments. As with the yield issue, multi-tags allow us to ignore damaged tags and statistically rely on the promise that enough multi-tags will remain operational to satisfy an application's requirements. This property of multi-tag systems helps to improve the overall reliability and cost of deployed multi-tag RFID systems.

10.3 RFID Demand Drivers

A strong driver of cost in RFID systems is the scope of the demand for this technology. With increases in demand, the number of produced RFID units will increase, which drives the amortized development costs down. However, many companies are hesitant to deploy RFID technology because the business case is not entirely clear or proven. This classic "chicken and egg" dilemma has inhibited the massive deployments of RFID systems so far. With improvements in RFID technology, the cost of RFID systems should decrease, creating a more convincing business case for companies and accelerating the demand for the technology, which will in turn reduce the amortized cost of RFID tags even further. The demand for RFID will be driven by many companies with a wide range of specializations and fields, led by major players such as Wal-Mart and DoD, and the desire to remain competitive in rapidly evolving marketplaces. Consequently, companies will experience mounting pressures to adopt RFID technology, and multi-tag -based strategies will help bootstrap undecided companies into this technology and help propel them into the RFID age.

10.4 Cost Effective Tag Design Techniques

Overall tag cost can be reduced by developing better and cheaper tag components and assembling them in a more cost-effective manner. We give some practical examples of advanced memory design, antenna design, and assembly technologies to illustrate how technological developments drive down RFID costs. The cost of RFID tags can be reduced through innovative lower-cost memory design technologies. For example, the chip manufacturer Impinj Inc, uses "self-adaptive silicon", which enables the low-cost reliable analog storage of bits in floating gates [24]. Another way to decrease the tag cost is to speed up the tag manufacturing and packaging processes. For example, Alien Technology has developed "Fluidic Self Assembly" (FSA), which allows for the placement of a large number of very small components across the surface in a single operation, significantly speeding up tag assembly. This technology involves flowing tiny microchips in a special fluid over a base containing holes shaped to catch the chips [3]. In addition to designing antennas with improved receptivity and orientation, measures can be taken to lower antenna costs. For example, Symbol Technologies reduced the cost of antennas by manufacturing them out of aluminum rather than silver. The company also compressed antennas into small, low-powered inlay, thus reducing tag area and cost [48].

10.5 Summary of Multi-Tag Economics

RFID technology leverages Moore's Law in the positive direction. RFID tags are getting both smaller and cheaper over time, resulting in a multiplicative corresponding reduction in tag cost.

In addition, RFID tag yields are improving, further compounding the effect of these trends on cost reduction. Also, engineering and manufacturing tolerances for RFID chips are much larger than for high-end chips (e.g., RFID chips can operate at low clock speeds, extreme miniaturization is not a prominent problem in RFID production, etc.). Moreover, the VLSI manufacturing equipment for RFID tags does not have to be cutting-edge, which reduces the cost pressure when constructing tag fabrication facilities. Rapidly increasing demand for RFID, along with cheaper manufacturing techniques and improving yields, is expected to rapidly bring the cost of RFID tags into the sub-penny levels in the near future, making multi-tags ever more affordable. In short, multi-tags are clearly economically viable, and their benefits are bound to become even more dramatic over time.

11 Conclusion

There are many obstacles to reliable RFID-based object identification. Environmental conditions such as temperature and humidity, ambient radio noise, and object geometries and occlusions can significantly interfere with object detection and identification. Dramatic variations in tag receptivity and detectability, even among tags of the same type and production batch, reduce the reliability of tag detection. The metals and liquids present in or around objects (or in the environment) can reflect or absorb radio signals, thus preventing accurate signal decoding. In addition, the object density, concentration, and placement geometry can adversely affect object detection.

To overcome these obstacles, we proposed tagging objects with multiple tags. We showed that multi-tags are very effective in dealing with radio noise, tag variability, and the presence of metallics and liquids among objects, as well as high object densities. We gave examples of numerous applications that could greatly benefit from multi-tags. We addressed the economics of multi-tags and argued that multi-tags are cost-effective even today for many cost-sensitive, safety-critical, and security-oriented applications. We predicted that multi-tags will become cost-justifiable for many additional applications in the near future, as the cost of passive tags continues to drop rapidly. We also stressed the importance of careful RFID system design to ensure the desired operation and performance.

In summary, we believe that multi-tag RFID technology promises many benefits to numerous applications, and will expedite reductions in tag manufacturing costs. This will positively tip the cost-benefit scale in favor of massive RFID deployments, and encourage many companies, organizations, and communities to join the age of ubiquitous RFID.

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