Multi-Tag Radio Frequency Identification Systems*

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Abstract

We propose and analyze the effects of attaching more than one RFID tag to each object. We define different types of multi-tag systems and examine their benefits, both analytically and empirically. We also analyze how multi-tags affect some existing tag singulation algorithms. We show how multi-tags can serve as security enhancers, and propose several new promising applications of multi-tags, such as preventing illegal deforestation.

1. Introduction

Radio Frequency Identification (RFID) is a promising technology that supports numerous useful applications (e.g., supply chain management, inventory tracking, access control, and library book checkout, etc.). RFID is expected to soon replace bar codes, yet high tag cost, detection issues, and privacy concerns still impede the wide deployment of this technology [5]. A typical RFID system consists of readers, tags, and back-end servers that receive and process the information that the readers obtain from the tags. There are three types of RFID tags: active, passive, and semi-active. Active tags can initiate transmission on their own. Passive and semi-active tags rely on power from a reader to engage in a communication. Semi-active tags have batteries on-board, but they are used only for on-board computations.

There are two coupling mechanisms used by passive and semi-active 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 their own 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.

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Previous works on RFID technology assume that an object is tagged with a *single* tag [5]. In this paper we propose the idea of tagging each object with *multiple* tags. We show that having multiple tags per object can be very beneficial, as well as cost-justifiable for certain applications. Some of the benefits of multi-tags that we envision include increased induced voltage on a tag, increased communication range between the reader and a tag, increased tag memory per object, and increased overall availability, reliability, and durability of the system. Multi-tags can also play an important role in the security of the system and, depending on the type and complexity of the tags, they may even engage in inter-tag communication.

The rest of the paper is organized as follows. In Section 2 we define several different types of multi-tags. In Section 3 we present our analysis of multi-tag systems and discuss the results. In Section 4 we analyze the effects of multi-tags on some tag singulation algorithms. In Section 5 we show that multi-tags can enhance security. In Section 6 we address the costs and benefits of multi-tags. In section 7 we give examples of applications that will benefit from the use of multi-tags, and in Section 8 we conclude with future research opportunities.

2. Definitions

We define three broad types of multi-tags:

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

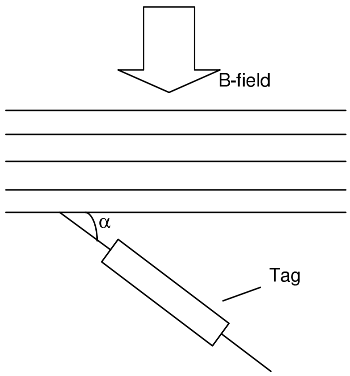
II. *Dual-Tags* - two tags connected to each other and having one or two antennas;

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

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

Type-IIc - both tags have their own memory and they also have shared memory;

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



$V_0 = 2\pi fNSB_0 \cos\alpha$

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

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

3. Our 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 that the tag makes 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 [8]. 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 which induces many of the benefits of multi-tags, namely the expected incidence angle of the arriving signal.

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 hence 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 $voltage \sim \sin^2(\beta)$ [3] [13] [5]. So, for both inductive coupling and for 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 to one of the tag antennas. We assume a uniform distribution for the signal arrival direction. 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 pair-wise 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 the them parallel to the faces of a tetrahedron, a platonic solid.[1]

The second question asks what is the actual expected maximum incidence angle of the arriving signal with respect to the antenna 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. 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:

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

The expected incidence angle for two tags is:

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

1 For five or more tags, it becomes more complicated to 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, etc.

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

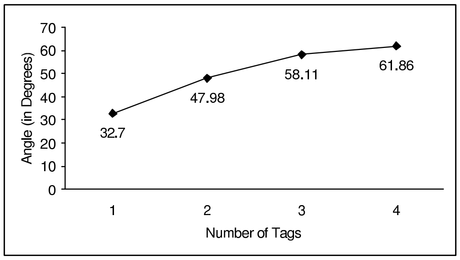


Figure 2. Expected largest incidence angle to any tag.

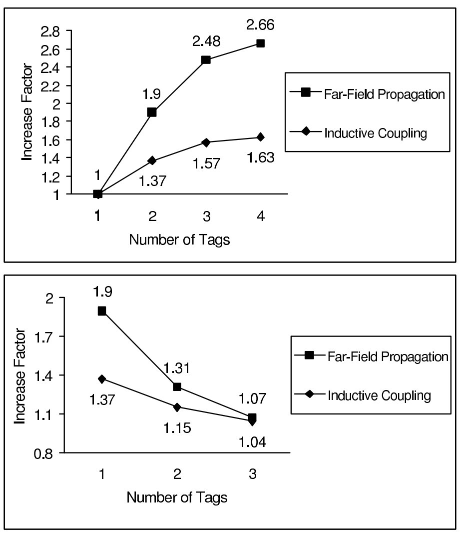


Figure 3. Absolute and relative induced voltage increase on the tags.

To calculate the expected angle of incidence, our simulator generates a random uniformly-distributed point on the surface of a sphere [9]. 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 2 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.

Figure 3 shows the absolute and relative voltage improvements for various multi-tag ensembles. Figure 4 shows the expected factor of voltage relative to the largest voltage which is attained when the angle is 90 degrees (i.e., when $\sin(\beta) = 1$ is maximized). Figure 5 depicts the expected communication range increase for inductive coupling technologies as the number of tags is increased, and also for far-field propagation scenarios. These values were computed based on the relation of the distance between a reader and a tag, and the voltage generated by the reader. For backscattering technology, the effective communication distance varies as $\sim \sqrt{voltage}$; for inductive coupling, the maximum communication distance varies as $\sim \sqrt[6]{voltage}$ [10].

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.

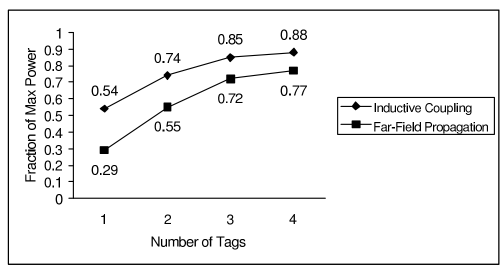


Figure 4. Expected attainable power factor relative to the maximum power (90 degrees).

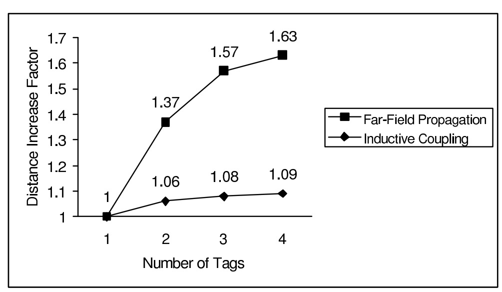


Figure 5. Expected factor of communication range increase.

4. Effects on Singulation Algorithms

Singulation algorithms allow a reader to uniquely identify tags while avoiding tag broadcasting collisions (i.e., simultaneous interfering transmissions). We analyze the effect of multi-tags on existing singulation algorithms, namely two variants of Binary Tree-Walking [7] [5], Slotted-Terminating Adaptive Collection (STAC) [2], Slotted Aloha [5], and Randomized Tree-Walking [1] [15] [4]. First, we note that dual-tags will have no effect on the singulation algorithms if for a given query the tags agree on a single combined response. While dual-tags do not have to generate two separate responses, this may be an option for some systems. The following algorithm illustrates how dual-tags can agree on a single responder and thereby utilize the resulting power benefit for one of the tags.

```
                Request
Reader    -------------------->  Tag1, Tag2
                Data1, Power1
Tag1      -------------------->  Tag2
                Data2, Power2
Tag2      -------------------->  Tag1

Tag1:     if(Data1 == Data2) {
             if(Power1 >= Power2) {
                       Data1
                Tag1 ------------>  Reader
             }
          }
          else {
                       Data1, Error
                Tag1 ------------>  Reader
          }

Tag2: Same procedure as Tag1 (probability
      that the Power1 == Power2 is small).
```

The rest of the analyses focus on redundant tags. We combine the analysis of the effects of redundant tags on singulation algorithms with a brief description of each algorithm, and Figure 6 summarizes these analyses.

4.1. Effect on Binary Tree-Walking

In binary tree-walking algorithms, tags are assumed to be located at the leaves of a tree. The reader performs a tree-walk beginning at the root, and requiring only tags in specified sub-trees to respond. In one variant of this algorithm, the reader selects tags based on an ID prefix and each tag responds with the next bit [12] [7]. In another variant, the tags respond with the part of their IDs that follows the given prefix [5]. In both cases, bits are likely to be encoded using Manchester bit encoding [5], resulting in no collisions between identical tags. The Manchester scheme encodes 1 as a rising signal, and 0 as a falling signal. When a collision occurs, a reader will hear a constant high signal. If both tags send the same bits, no collisions will be detected. Therefore, the time it takes for the reader to identify N objects is independent of whether the system has redundant tags or not. Redundant tags will not force the algorithm to explore additional branches of the binary tree, and they do not add new tags that have to be identified. Thus, redundant tags have no adverse effect on binary tree-walking algorithms.

4.2. Effect on Randomized Tree-Walking

In the Randomized Tree Walking Algorithm described in [15], each tag generates a random number, and a tree walking algorithm is performed on these random numbers. Once a tag is selected based on its random number, the tag transmits its real-ID over the backward channel, which a passive adversary can not hear, thus providing security for real-IDs. If the reader wishes to singulate objects with k redundant tags per object, the singulation time will take slightly longer than k times that of a conventional single tag system. In addition, the reader or the back-end server will need to filter out duplicates.

4.3. Effect on STAC and Aloha Algorithms

In the Slotted-Terminating Adaptive Collection (STAC) singulation algorithm [2], tag identification proceeds in rounds with each round consisting of time slots. The reader supplies a hash function to the tag, which uses it to compute its pseudo-ID, which in turn determines the time slot in which the tag will transmit its ID. If several tags collide in a slot, they retransmit their IDs in the next round, in a slot chosen using a different hash function. Selected tags may respond in a special first slot of each round to avoid collisions with unsingulated tags.

Redundant tags increase the identification time of N objects since each tag has to be identified separately. Most importantly, the tag data and/or STAC algorithm have to be modified slightly to accommodate redundant tags. If the STAC algorithm is not modified, the redundant tags will always collide by transmitting in the same slot during each round, because the hash value that is based on the tag data will be identical for all redundant tags, independently of the hash function provided by the reader. A simple remedy to this problem is to add several unique bits to each tag to ensure that they are distinct, and then to use these unique bits for slot selection. However, this modification can complicate tag manufacturing. Note that in the STAC algorithm, redundant tags can cause a denial of service (DOS) situation by preventing the algorithm from identifying a tag. Redundant tags can prevent an individual single object from being identified, whereas a blocker tag [7] in binary tree traversal can block a whole sub-tree of objects.

In the similar Slotted Aloha algorithm [5], each tag has a random number generator on-board, which is used to determine the response slot for a tag. As a result, redundant tags will eventually select distinct response slots. Consequently, no additional bits on-board the tags are necessary, significantly simplifying the manufacturing process and the algorithm's operation.

4.4. Summary of Singulation Issues

From the analysis of the singulation algorithms above, we conclude that dual-tags are very useful and have no negative timing effect when the tags form a single response to a given query. Also, redundant tags are most efficient when Binary Tree-Walking algorithms are used. These results are summarized in Figure 6.

Algorithm	Redundant Tags	Dual-Tags
Binary	No Effect	No Effect
Binary Variant	No Effect	No Effect
Randomized	Doubles Time**	No Effect*
STAC	Causes DOS	No Effect*
Slotted Aloha	Doubles Time**	No Effect*

Figure 6. Effect of redundant and dual-tags on singulation algorithms.
*** Assuming dual-tags form a single response**
**** Assuming two redundant tags per object**

5. Multi-Tags as Security Enhancers

Security in RFID Systems has been well-studied. From access control schemes [16] to reader-tag mutual authentication protocols [4], most RFID security approaches share a common goal, namely to provide security guarantees using minimal hardware. The technique we propose for multi-tags shares this goal.

Multi-tags can provide enhanced security using the idea of "chaffing and winnowing" [11]. Chaffing and winnowing is different from steganography and encryption, the traditional means of achieving confidentiality. 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.

The idea of using chaffing and winnowing for achieving secrecy was noted in [15]. However, it presumes that readers will transmit chaff, thereby confusing eavesdroppers. With multi-tags, the extra tag(s) can be used to create chaff, hiding the real identity of the tag and consequently of the object. Sending chaff probabilistically, or controlling the amount of chaff sent will hide the real number of tags in the reader's interrogation zone. Chaff can be generated by the tags, stored on the tags during manufacturing, or supplied to the tag by the reader. On the other hand, chaffing and winnowing may increase the manufacturing cost of the tag due to the extra chaff-related functionality, and create additional computation overhead and delay associated with chaff generation and filtration.

6. Benefits and Costs

From the multi-tags analysis above, we see that the expected voltage on the best-oriented tag is increased, which allows for increased tag circuit functionality and/or higher expected detection range. Additional benefits of multi-tags are described below.

Dual-tags double the amount of memory available per object. This extra memory can be used to reduce the contention for resources and to further strengthen security in systems that use one-time pad techniques [6] (i.e., additional memory will enable more secrets to be stored). Availability of the system is likely to improve, since even if one tag is unintentionally shielded by a material that absorbs or reflects radio signals (e.g., as is the case with shopping carts containing metalic and liquid-filled containers), the second or third tag may still be able to pick up the reader's signal and respond.

A multi-tag system is also more reliable, because if one tag fails, is deliberately/illegally removed, or accidentally falls off, the other remaining tags will still be present and functional. In some multi-tag systems the failure of a tag can be made detectable. For example, in the case of dual-tags, if one tag fails to communicate with the other tag, the working tag can still send an appropriate error signal to the reader, indicating that one of the tags has failed and requires a replacement. In the case of redundant tags, a possible failed-tag error can be detected if a reader does not receive a response from all the redundant tags. A probable tag failure can be detected, if over a period of several reads, not all the redundant tags respond correctly.

Multi-tag systems admittedly have a higher cost compared to the single-tag systems, including increased manufacturing cost and potentially longer singulation time, but the benefits described above will outweigh the costs for many applications. Given the rapidly decreasing price of RFID tags, multi-tags systems will become increasingly economically viable over time. Some applications that may benefit from multi-tags even today are presented next.

7. Applications

Any application requiring higher availability, reliability, durability, induced tag voltage, or increased communication range can benefit from our proposed multi-tags framework. For example, supply chain management applications can benefit from increased object detection probability, which is crucial in that arena. Retailers of goods with small profit margins could better track their inventories and improve checkout procedures, which would translate into increased income.

Despite the expected cost increase associated with implementing multi-tags, some multi-tag applications could realize direct cost benefit. For example, if an object crosses international borders and must be identified by readers working at different frequencies, or using different singulation algorithms, it may be more expensive to add extra functionality to the existing tags, rather than using additional multi-tags, each dedicated to a particular frequency, algorithm, or region. Luggage tracking at airports is an example of such a scenario.

Another intriguing and useful application of multi-tags could be the prevention of illegal deforestation by embedding tags in the trunks of trees. Since tags are very cheap compared to the cost of large pieces of lumber (especially for rare or legally-protected trees such as Redwoods), the economics of this application are financially viable. When logs are shipped and sold, they will 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 expensive for illegal loggers to detect and remove all the tags from a given tree trunk, thus substantially increasing the cost and risk of illegal deforestation, at a relatively low cost to the protecting agencies. While wood contains water which absorbs radio signals, the use of multi-tags in this scenario would increase the detection probability, thus alleviating some of the usual issues of tree tagging [14]. While the idea of tagging trees is in itself not new [14], our proposed scheme of multi-tagging trees/lumber, as well as the application of preventing illegal deforestation, seem not to have appeared in the literature before.

8. Conclusions and Future Work

We have introduced multi-tag systems, where several RFID tags are attached to each object. Our analyses indicate that multi-tags increase the expected induced voltage in a tag, which improves the effective operational range of the system. Moreover, multi-tags add memory per object, and improve availability, reliability, durability, and security. We also analyzed the interaction of multi-tags with existing singulation algorithms, and suggested new applications that can benefit from multi-tags (e.g., preventing illegal deforestation). We believe that there are many practical scenarios where multi-tags will be beneficial as well as economically viable despite the modest increases in cost and interrogation times.

Future research on multi-tags includes the practical field-testing of multi-tags, identifying additional promising applications, and the development of additional theory and algorithms for different types of multi-tag systems. On the security front, cooperation among multi-tags can be very effective and may yield yet undiscovered security benefits.

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