Efficient Pinpointing of Misplaced Tags in Large RFID Systems

Kai Bu†, Bin Xiao†, Qingjun Xiao†, Shigang Chen‡
†Department of Computing, The Hong Kong Polytechnic University
Email: {cskbu, csbxiao, csqjxiao}@comp.polyu.edu.hk
‡Department of Computer & Information of Science & Engineering, University of Florida
Email: sgchen@cise.ufl.edu

***Abstract*—The Radio-Frequency Identification (RFID) technology has stimulated many innovative applications. Misplaced-tag pinpointing (MTP) is important to RFID applications in production economics because optimal inventory placement can significantly increase profit. Previous research from the database perspective needs to process a large amount of data which is time-consuming to collect (and energy-consuming if active tags are used). How to efficiently address the MTP problem from the protocol design perspective however has not been investigated. In this paper, we propose a series of protocols toward efficient MTP solution in large RFID systems. The proposed protocols detect misplaced tags based on reader positions instead of tag positions to guarantee the efficiency and scalability as system scale grows, because the number of readers is much smaller than that of tags. Considering applications to employ more and more popular active tags, we further propose a solution requiring responses from only partial tags in favor of energy saving. We analyze the optimal performances of proposed protocols to demonstrate their efficiency potential and conduct extensive simulation experiments to evaluate their performance under various scenarios. The results show that the proposed protocols can significantly increase the time efficiency and the energy efficiency by over 70% on average when compared with the state of the art.**

I. Introduction

The Radio-Frequency Identification (RFID) technology has brought many practically innovative applications to various fields, such as supply chain management [1], target tracking [2], forest search and rescue [3]. To support these applications, plenty of research effort has been devoted to addressing important problems in RFID systems (e.g., cardinality estimation [4], [5], finding popular categories [6], missing-tag identification [7], misplaced-tag pinpointing [8], and secure communication [9]). In this paper, we concentrate on one of these important problems, namely Misplaced-Tag Pinpointing (*MTP*), especially in large RFID systems.

The MTP problem aims to detect and pinpoint tags attached to misplaced inventory items in a large warehouse, retailing store, shipside, or airport. The statistics in [10] shows that consumers of a leading retailer cannot find on average 16% of inventory items in the stores because those items are misplaced. Countermeasures to mitigate misplacement errors keep being one of the primary concerns in production economics. Optimal inventory placement can increase profit by even up to 8.1% [11]. Such an increase would yield $1.1 billion more profit for Wal-Mart, the world's largest retailer [8]. Rekik *et al* suggested that the RFID technology can be adopted to reduce inventory misplacement errors [12]. However, Hong Kong International Airport, one of the largest airports in the world and one of the earliest RFID system consumers, still loses more than $20 million annually to relocate misplaced and mis-transported bags [13]. One significant application is thus to pinpoint misplaced items for the purpose of replacement.

Recently, a database-oriented method called RPCV has been proposed to find misplaced items in retail [8]. In RPCV, one reader controls many antennas each of which corresponds to one position. RPCV requires inventory items to be placed exactly following layout plans and represents each tag attached to an inventory item as a two-dimensional vector. A tag vector includes the number of readings both by the right antenna (i.e., whose corresponding position covers where the item attached with the tag should be placed) and by wrong ones. Then RPCV finds misplaced tags by processing all tag vectors. RPCV focuses more on computational efficiency because it processes large databases of items. Practically, it is laborious and challenging to place inventory items exactly in accordance with layout plans. Furthermore, collecting information from all tags in a large RFID system is very time-consuming as discussed in [13] and our previous work [14]. Therefore, the concern of time efficiency may outweigh that of computational efficiency. Upon closer inspection, when active tags are employed, RPCV cannot take into consideration both methodology accuracy and energy efficiency. The reason is that it requires each tag to respond dozens of times for finding misplaced items whereas too many tag responses cost active tags a lot of energy [5].

Departing from previous research, this paper investigates efficient MTP solution from the perspective of protocol design. Particularly, we target at designing protocols to time-efficiently and energy-efficiently collect information for detecting and pinpointing misplaced tags. We achieve this target primarily through using reader vectors and requesting responses from partial tags. First, to increase time efficiency, we detect misplaced tags using a reader vector. The intuition is that misplaced tags in a category must exist when separate clusters of readers cover tags in this category. Reader cluster construction based on the reader vector will be explained later in this paper. It takes much less time and much fewer tag responses to form reader vectors than does RPCV forming tag vectors. Thus both time efficiency and energy efficiency can be increased.

Interestingly, the size of reader vectors is also smaller than that of tag vectors mostly due to the deployed readers is much fewer than tags. Second, to address the MTP problem more energy-efficiently, we further investigate a solution that forms reader vectors without enforcing all tags to respond.

Summing up, this paper makes the following major contributions to efficient MTP solution in large RFID systems.

❏ Investigate Basic MTP protocol (*B-MTP*) based on tag-wise positioning, which requires each tag to be located. A heuristic reader activation method is proposed to accelerate MTP protocols. Compared with RPCV [8] to form tag vectors, B-MTP has less overhead to collect information for tag positioning. However, we demonstrate the inefficiency and unscalability of B-MTP in large RFID systems through performance analysis and indicate the demand of more efficient MTP solutions.

❏ Propose a Time-efficient MTP protocol (*T-MTP*) toward high time efficiency through eliminating tag-wise positioning. T-MTP detects misplaced tags using reader vectors instead of tag vectors. Only misplaced tags need to be located. The performance analysis demonstrates that T-MTP can also improve the energy efficiency when compared to B-MTP.

❏ Propose an Energy- and Time-efficient MTP protocol (*ET-MTP*) to further enhance energy efficiency through enforcing only partial tags to send responses.

❏ Analyze the best performances of proposed protocols to indicate their efficiency potential and conduct extensive simulation to evaluate their efficiency under various scenarios. The results show that the proposed protocols can significantly outperform the-state-of-the-art RPCV for increasing time efficiency and energy efficiency by over 70% on average.

The rest of this paper is organized as follows. Section II defines the problem and the system. Section III discusses basic MTP protocols and indicates their limitations through performance analysis. Section IV and Section V present efficient MTP protocols toward high time efficiency and high energy efficiency, respectively. Section VI reports the simulation results. Finally, Section VII draws the conclusion.

II. System Model

This section provides an overview of the MTP problem. We formulate the problem under necessary and reasonable assumptions and discuss performance metrics for evaluation.

A. Problem Overview and Assumptions

Consider a large RFID system comprising a set of readers $R = \{r_1, \ldots, r_i, \ldots, r_m\}$ and a set of tags $T = \{t_1, \ldots, t_j, \ldots, t_n\}$. The readers are deployed at known positions to provide position reference for positioning tags. We also call them as *reference readers* in this paper. Each tag has a unique ID and attaches to an inventory item. Hereafter in this paper, we use terms *inventory item* and *tag* interchangeably. The tags could be either passive or active according to specific system requirements. Inventory items are placed by categories, that is, a category of inventory items should be properly placed together in a certain area, but not required to strictly follow any layout plans. One section of the tag ID, called *category ID*, specifies the category of the inventory item attached with the tag [6]. The set of distinct category IDs is denoted as $C = \{c_1, \ldots, c_k, \ldots, c_u\}$. We denote by A_k the area where tags in the category of c_k should be placed. A tag of category c_k is viewed as being misplaced if it locates away from A_k. The MTP problem is to pinpoint misplaced tags. Although some tags could be misplaced, a majority of tags in each category are still properly placed in practical. Once misplaced tags are pinpointed, one can directly walk toward or use navigation methods such as [15] to approach them for replacement.

We assume an inventory item list in accordance with all present items is maintained on a backend server that executes the MTP protocol. The list is updated when new items are moved into the system or present items are moved out. Considering that tags may be stolen by misbehaving workers or customers, missing-tag identification methods such as [7] can be adopted to timely detect and identify the missing tags. The records corresponding to identified missing tags should be immediately deleted from the list.

To achieve accurate tag positioning, we assume that the representative RFID positioning scheme in [16] is adopted. In this scheme, a reader has a set of transmission power levels [17]. The communication radius corresponding to a power level can be obtained by an RF site survey using a positioning device and radio signal strength measurement device as in [18] or a set of reference tags deployed at known positions as in [16]. For simplicity, communication radii corresponding to transmission power levels are hypothetically provided. Without loss of generality, we consider scenarios that readers are deployed on the ceiling of the system. Distance measurements to at least $h \geq 3$ reference readers are needed to locate a tag. Note that theoretically it requires distance measurements to at least four reference readers to locate a tag in 3D space [19]. Combining the implicit constraint that a tag cannot be placed higher than the height of the system, $h = 3$ however is the least requirement for the basic positioning scenario in [16].

Finally, we consider MTP scenarios that readers follow sequential reading and tags keep stationary. First, it surely will be more complicated when multiple readers read tags in parallel, because of the reader-reader collision problem [18]. The reader-reader collision problem occurs when two readers covering common tags are active to read the tags at the same time. Query messages from two readers will collide and thus the tags will not send any response. Therefore the reader-reader collision problem may mislead detection of misplaced tags. Although simultaneously activating readers with disjoint covering region can avoid the reader-reader collision problem [18], it is still very challenging to achieve this with readers frequently adjusting transmission power levels for tag positioning. Second, when mobile tags exist, being away from the supposed area solely cannot verify a misplaced tag. We need to further verify that if the tag is carried by moving machines or wandering customers. In this paper we try to concentrate on scenarios not that complicated but generalized enough to acquire insights for designing efficient MTP protocols. Scenarios allowing parallel reading or even mobile tags are left for our future work.

B. Performance Metrics

We consider two performance metrics, *the execution time* and *the number of tag responses*, for evaluating MTP protocols's time efficiency and energy efficiency, respectively.

1) The execution time shows the time efficiency, which is highly desired for an MTP protocol to be scalable as RFID system scale becomes large. Almost all RFID research considers the time efficiency as a primary concern, such as tag identification [13], [20], [21], cardinality estimation [4], [5], and missing-tag identification[7].

2) The number of tag responses indicates the energy efficiency of MTP protocols. Active tags are expected to significantly impulse the growth of RFID applications because of their ability of initiating communication and hundreds-of-feet communication radius, which is much longer than that of passive tags. However, active tags depend on self-equipped battery to enable any operation. Thus, during enjoying the improved system performance brought by active tags, the energy cost should be as low as possible by controlling the number of tag responses [5].

III. Preliminary and Basic MTP Protocols

This section discusses B-MTP based on tag-wise positioning that requires each tag to be located. We analyze B-MTP's performance and limitations to indicate the demand for more efficient MTP protocols in large RFID systems.

A. B-MTP Design

Intuitively, if all tags have been located, it is straightforward to determine whether any and where tags are misplaced. Using position estimations of tags in the category of c_k, we can easily bound the area A_k. Any tags in the category of c_k but out of A_k are detected as misplaced ones, which should be replaced.

Based on the above intuition, we investigate two B-MTP designs, namely Individual Positioning based B-MTP (*IPB-MTP*) and Collision Arbitration based B-MTP (*CAB-MTP*). They differ from each other in tag-wise positioning process.

1) IPB-MTP Design. IPB-MTP locates tags in n rounds each of which is dedicated to locating one tag. In each round, readers are sequentially activated to broadcast a query message containing a tag ID (recorded in the inventory item list) and wait for the tag's response. Receiving a tag response indicates that the tag is within the reader's covering region corresponding to current transmission power level. A round ends when each of h readers has determined the minimum transmission power level l_{min} for it covering the tag. The communication radius corresponding to l_{min} for a reader r_i covering a tag t_j is regarded as the distance measurement d_{ij} between r_i and t_j. A representative RFID positioning scheme in [16] estimates the position of t_j as follows:

$$
\begin{aligned}
&(x_{tj}, y_{tj}, z_{tj}) = \underset{(x_{tj}, y_{tj}, z_{tj})}{\arg\min} \sum_{i=1}^{h} (\frac{d_{ij} - \hat{d_{ij}}}{d_{ij}})^2, \\
&\text{s.t. } z_{tj} \leq H; \\
&\qquad \hat{d_{ij}} = \sqrt{(x_{ri} - x_{tj})^2 + (y_{ri} - y_{tj})^2 + (z_{ri} - z_{tj})^2},
\end{aligned} \tag{1}
$$

where (x_{ri}, y_{ri}, z_{ri}) denotes the known position of a reference reader r_i, (x_{tj}, y_{tj}, z_{tj}) the position estimation of a tag t_j, and H the height of the system. Its best performance can limit the position error to less than 5% of the longest edge of the system [16]. We omit the computation time of solving Equation 1 in the execution time considering the stunning processing power of current computers.

To speed up MTP protocols, we use a heuristic method to activate readers rather than always following the ordering defined in the set R. The heuristic stems from the truth that if a reader r_i receives a response from a tag t_j then 1) readers near to r_i have higher probabilities to cover t_j than those far from r_i; and 2) it is usually faster to find the readers that cover tags in the same category with t_j when starting from readers near to r_i than starting from those far from r_i. Let $S_{RR} = \{r_{r1}, \ldots r_{ri}, \ldots\}$ denote the set of reference readers covering a to-be-located tag. It costs on average $m/2$ time slots to find r_{r1} following the ordering in R. Then each of the other r_{ri} has great potential to be heuristically found using only one time slot. The heuristic reader activation method can collect S_{RR} for a tag within about $m/2 + h - 1$ time slots. Collecting S_{RR} without the heuristic method, however, will take $hm/2$ time slots on average, averagely requiring $m/2$ time slots to find each of the h reference readers.

2) CAB-MTP Design. CAB-MTP first sequentially activates each reader to read tags in its covering region. Then tags covered by at least h readers can be located. For tags covered by less than h readers, we find other reference readers through heuristically activating readers near to those in the tag's S_{RR} with increased power level.

The challenge is that a reader cannot simultaneously receive responses from multiple tags due to the tag collision problem [18]. The tag collision problem occurs when multiple tags covered by a reader respond at the same time. Two typical categories of collision arbitration protocol, which aims at scheduling tags to respond in a collision-free manner, are slotted Aloha [20], [22] or Tree-traversal [23], [24].

We design CAB-MTP using slotted Aloha because it can yield higher efficiency in large systems than Tree-traversal [13]. We hereby briefly review the basics of slotted Aloha based collision arbitration protocols to keep the paper self-contained. Using slotted Aloha, the reader sends a query frame with a certain number of time slots (*frame size*) and each tag picks up a random time slot to respond. A time slot chosen by no tag, only one tag, or multiple tags is usually called an *empty slot*, a *singleton slot*, or a *collision slot*, respectively [21]. The reader can correctly receive the tag response only in a singleton slot; it has to continuously send new frames with adjusted frame size until no collision occurs.

Observing slotted Aloha not including tag IDs in query messages, one may conjecture that CAB-MTP executes faster than does IPB-MTP. Unfortunately, different from single-reader scenarios, each tag should still include the ID in its response. In a single-reader scenario where the only reader covers all tags, given all tag IDs, the reader can determine exactly which tags respond in which time slot. Thus, there is no need to transmit tag IDs in either query messages or responses. In multi-reader scenarios, on the other hand, it is challenging to precisely and timely track tags covered by each reader, although we have all tags recorded. Therefore, CAB-MTP requires tag IDs to be included in responses. Otherwise, even when no collision occurs, a reader still cannot ensure exactly which tag responds if more than one tags are supposed to respond.

B. Performance Analysis and Limitations

***Remark** 1:* A lower bound of the number of tag responses N_{B-MTP} and the execution time T_{B-MTP} for B-MTP to pinpoint misplaced tags is as follows:

$$N_{B-MTP} = hn,$$
$$T_{B-MTP} = hnt_{id},$$

where t_{id} denotes the transmission time of the tag ID.

We derive Remark 1 as follows. Because B-MTP requires each tag to respond to at least h reference readers for tag positioning, the total number of tag responses for locating all tags is at least hn. Corresponding to each tag response, the tag ID should be contained either in the query message by IPB-MTP or in the response by CAB-MTP . Then the execution time costed by each tag response is at least t_{id}. Therefore, the total execution time of B-MTP is at least hnt_{id}.

The lower bound in Remark 1 however is hardly achievable mostly due to two reasons. First, besides transmission of the tag ID, transmission of the tag response when using IPB-MTP or the query message when using CAB-MTP takes additional time, although which is tiny when compared with t_{id}. Note that we will omit this additional time cost in the following analysis. Second, further communication between reference readers in S_{RR} and the to-be-located tag for determining l_{min} also induces additional overhead.

Next we will analyze the optimal performances of IPB-MTP and CAB-MTP, respectively, to indicate how close they can approach the lower bound.

***Remark** 2:* The optimal number of tag responses $N_{IPB-MTP}$ and the optimal execution time $T_{IPB-MTP}$ for IPB-MTP to pinpoint misplaced tags are as follows:

$$N_{IPB-MTP} = hn,$$
$$T_{IPB-MTP} = 2hnt_{id}.$$

We derive Remark 2 as follows. Suppose that r_{ri} successfully receives t_j's response at transmission power level l_{temp}. The best case for r_{ri} to determine l_{min} is when l_{temp} happens to be l_{min}. In this case, t_j cannot hear r_{ri} when r_{ri} sends a query message at transmission power one level lower than l_{min}. Then t_j will not send any response. As each reference reader in a tag's S_{RR} needs to initiate at least one more query message containing the tag ID to determine l_{min}, it is straightforward that at least hnt_{id} more time is needed. Thus the optimal execution time of IPB-MTP should be $2hnt_{id}$. The optimal number of tag responses can reach hn as no tag response is induced by l_{min} determination in the best case.

***Remark** 3:* The optimal number of tag responses $N_{CAB-MTP}$ and the optimal execution time $T_{CAB-MTP}$ for CAB-MTP to pinpoint misplaced tags are as follows:

$$N_{CAB-MTP} = ehn,$$
$$T_{CAB-MTP} = (e+1)hnt_{id}.$$

We derive Remark 3 as follows. It shows in [13] that the highest efficiency of slotted Aloha is $1/e$ (i.e., optimally $1/e$ of the tags can be identified within one query frame), where e is the natural constant. CAB-MTP using slotted Aloha achieves the best performance when each tag is covered by at least h readers, each of which reads the tag at transmission power level l_{min}. Let n_{ri} denote the number of tags covered by a reader r_i. We have $\sum_{i=1}^{m} n_{ri} \geq hn$. Then the optimal execution time is derived by

$$(\sum_{i=1}^{m} en_{ri}t_{id}) + hnt_{id} \geq (e+1)hnt_{id}.$$

Furthermore, because all unread tags should respond to the query message and optimally $1-1/e$ of them will continue to respond to the following query message, the optimal number of tag responses is derived by

$$\sum_{i=1}^{m}(n_{ri} + (1-\frac{1}{e})n_{ri} + (1-\frac{1}{e})^2 n_{ri} + \ldots) \approx \sum_{i=1}^{m} en_i = ehn.$$

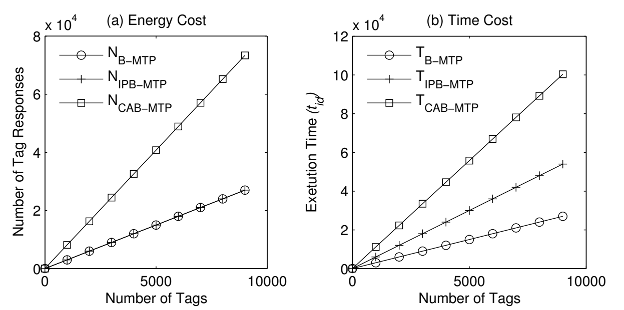

Fig. 1. Performance comparison of B-MTP, IPB-MTP, and CAB-MTP.

Figure 1 summarizes the performances of B-MTP designs claimed in Remark 1, Remark 2, and Remark 3, under the basic scenario when $h = 3$. IPB-MTP outperforms CAB-MTP because its optimal performance (especially the optimal number of tag responses) is closer to the lower bound. A major limitation of B-MTP designs is that their best performances are linear with respect to the system scale (i.e., the number of tags in an RFID system). This limitation not only hinders the protocol efficiency but also decreases the protocol scalability, especially in significantly large RFID systems. Next we will present two more efficient MTP protocols toward increasing time efficiency and energy efficiency, respectively.

IV. T-MTP: Time-efficient Misplaced-Tag Pinpointing Protocol

This section presents T-MTP and analyzes its performance as well as limitations. T-MTP enhances time efficiency trough eliminating tag-wise positioning when detecting misplaced tags. Only misplaced tags need to be located for replacement.

A. Motivation

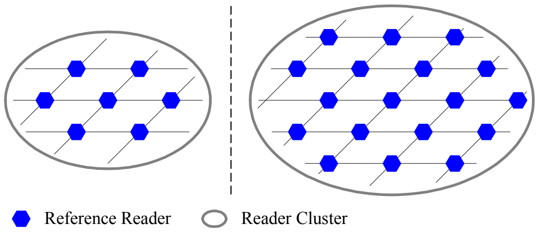

Fig. 2. Misplaced-tag detection using reader clusters. Tags covered by readers in the left smaller cluster are misplaced away from those covered by readers in the right larger cluster.

Reader positions rather than tag positions can also be used to detect misplaced tags. Figure 2 illustrates the intuition. In the illustrated scenario, readers are uniformly deployed. After all readers read tags in a category, two separate clusters of readers covering tags in the category are formed. Obviously the majority of this category of tags are covered by readers in the right cluster, which has a much larger cluster size (i.e., the number of included readers) than does the left one. The tags covered by readers in the left smaller cluster are therefore detected as misplaced tags and need to be located for replacement.

Considering that tag-wise tag positioning is a major factor limiting the efficiency of B-MTP, we believe that eliminating tag-wise positioning can yield promising efficiency gain. Next we will detail the design of T-MTP using the above idea.

B. T-MTP Design

T-MTP is expected to enhance time efficiency in two respects. First, adopting the aforementioned idea, one time slot is enough for a reader to determine if it covers any tags. This is because we can ensure that no tag or at least one tag is covered when the only time slot is an empty slot or not. Second, because we no longer require tag-wise positioning, tag IDs are unnecessary to be included in responses. Indices for differentiating misplaced tags in the same category could be used if more than one misplaced tags exist. For tag positioning, we need to further distinguish singleton slots from collision slots for determining the number of misplaced tags. In the Philips I-Code system [25], 10 bits, which is much shorter than the length of tag ID (usually 96 bits [26]), is enough to verify a collision.

T-MTP efficiently addresses the MTP problem in two stages, Time-efficient Misplaced-Tag Detection (*T-MTD*) and Pinpointing Information Collection (*PIC*).

1) Stage I: To detect misplaced tags in a category c_k, T-MTD sequentially activates each reader to determine if it covers tags of category c_k, using a same transmission power level and only one time slot. Specifically, a reader r_i first broadcasts a query message containing c_k and waits for tag responses. Upon receiving the query message, tags with c_k as the category ID respond with a 10-bit random bitstring. We use 0, 1, or 2 to denote the *slot state* of an empty slot, a singleton slot, or a collision slot, respectively. After each reader being active for one time slot, we form a vector V called *reader vector*, with the element $V[i]$ defined by

$$V[i] = \begin{cases} 0, & \text{if } r_i \text{ has an empty slot} \\ 1, & \text{if } r_i \text{ has a singleton slot} \\ 2, & \text{if } r_i \text{ has a collision slot} \end{cases} \quad (2)$$

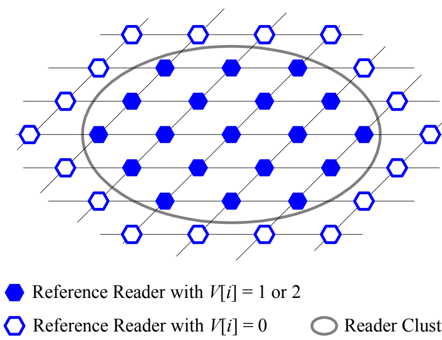

Fig. 3. Reader cluster construction using the reader vector V.

Using the reader vector V, T-MTD constructs *reader clusters*. A reader cluster consists of neighboring readers with $V[i] \neq 0$ surrounded by readers with $V[i] = 0$. Figure 3 illustrates an instance of reader cluster construction. The number of readers in a reader cluster indicates the cluster size. Intuitively, the largest reader cluster covers properly placed tags because a majority of tags in a category are supposed to be placed in the right area. Tags covered by readers in other smaller reader clusters are separated away from the right area and therefore are detected as misplaced ones.

2) Stage II: PIC further activates readers to collect enough information for positioning misplaced tags, which are detected in stage I. Required by Equation 1, the to-be-collected information is distance measurements between each misplaced tag and at least h reference readers. The activated reference reader broadcasts a query message containing category ID c_k by gradually tuning the transmission power level until l_{min} is determined. Then the communication radius corresponding to l_{min} is used as the distance measurement. Whether one or multiple misplaced tags are covered by a reader can be determined using the slot states of singleton and collision, respectively. PIC may further activate readers out of the smaller clusters to get enough distance measurements. We still prefer the aforementioned heuristic reader activation method (see Section III-A) for accelerating PIC.

C. Discussion of Misplaced-Tag Detection Error

T-MTD has no false positives but false negatives. First, T-MTD is false positive free because there must be some misplaced tags when multiple reader clusters exist. Otherwise T-MTD reports no misplaced tags when only one reader cluster is constructed. Second, T-MTD however may return false negatives when misplaced tags are not far away from the supposed area beyond a distance threshold. Specifically, the distance threshold is $2d_r$, where d_r represents the distance interval of uniformly deployed readers. Let $\min|(x_{tj}, y_{tj}) - (x_{ki}, y_{ki})|$ $((x_{ki}, y_{ki}) \in A_k.XY)$ represent the distance between a misplaced tag t_j and its supposed area A_k, where $A_k.XY$ is a set containing all (x, y) coordinates of positions within A_k. T-MTD may fail to detect misplaced tags satisfying the following constraint:

$$\min_{(x_{ki},y_{ki})\in A_k.XY} |(x_{tj}, y_{tj}) - (x_{ki}, y_{ki})| \leq 2d_r.$$

D. Performance Analysis and Limitations

***Remark** 4:* The optimal number of tag responses N_{T-MTP} and the optimal execution time T_{T-MTP} for T-MTP to pinpoint misplaced tags are as follows:

$$N_{T-MTP} = (\alpha(h-1)+1)n,$$
$$T_{T-MTP} = (um + \alpha hn)(t_{cid} + t_{10b}),$$

where t_{cid} denotes the transmission time of the category ID, t_{10b} the transmission time of 10-bit bitstring, and α the ratio of the number of misplaced tags to the number of tags.

We derive Remark 4 as follows. Because T-MTD does not need tag-wise positioning, the optimal case is when both the following conditions are satisfied:

- each tag is exactly covered by only one reader; *and*
- for a misplaced tag t_j, given current transmission power level l_{min} for readers that cover t_j, transmission power one level higher than l_{min} is enough for to-be-activated readers to cover t_j.

In the optimal case, PIC brings at least $h(t_{cid}+t_{10b})$ time cost and $h - 1$ tag responses for collecting enough information to locate t_j. Combining $um(t_{cid} + t_{10b})$ time cost and n tag responses for T-MTD forming the reader vector V, we therefore derive the conclusion in Remark 4.

Figure 4 plots the optimal performance of T-MTP under the scenario where $m = 50$, $u = 1000$, $h = 3$, and $\alpha = 0.05$, 0.10, 0.15, compared with that of B-MTP. In large RFID systems, it is ordinary that the number of tags in a category is more than the number of readers. Thus Figure 4 only shows curves subject to $n \geq um$. The length of the category ID is determined by $\log_2\lceil u\rceil = 10$ bits. Suppose that 96-bit tag ID is used. The transmission time t_{cid} and t_{10b} can be approximately represented by $10t_{id}/96$ and $10t_{id}/96$, respectively. As shown in Figure 4(b), T-MTP not only significantly decreases the execution time but also exhibits a much better scalability because T_{T-MTP} increases slightly as the system scale grows, when compared with B-MTP. Furthermore, T-MTP also outperforms B-MTP in higher energy efficiency because of less tag responses as shown in Figure 4(a).

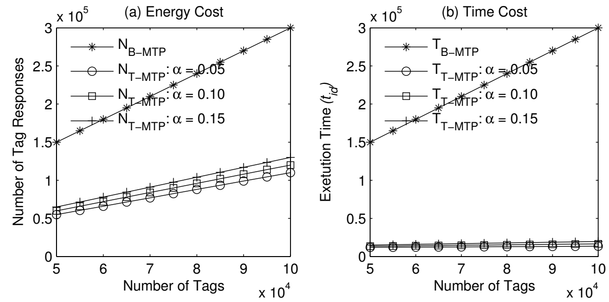

Fig. 4. Performance comparison of B-MTP and T-MTP.

Although T-MTP decreases the number of tag responses than B-MTP by a factor of

$$\frac{hn - (\alpha(h-1)+1)n}{hn} = (1-\alpha)(1-\frac{1}{h}),$$

it still causes a certain amount of unnecessary tag responses. The reason for this limitation is that whenever a reader reads a category of tags, all tags in this category will respond upon receiving the query message. However, two or more tag responses make no difference to distinguish a collision slot. Next we will present a more energy-efficient MTP protocol against such a limitation.

V. ET-MTP: Energy- and Time-efficient Misplaced-Tag Pinpointing Protocol

This section presents another efficient MTP protocol called ET-MTP. ET-MTP aims at further enhancing the energy efficiency while inheriting the time efficiency of T-MTP. We first discuss the basic idea of energy cost reduction and then detail protocol design and performance analysis.

A. Motivation

By the basic probability knowledge, when a reader covering n' tags broadcasts a query message and each tag responds with a probability p, we can expect pn' tag responses [5]. Similarly, when a reader receives a tag response, we can expect $1/p$ tags being covered. Thus, it is natural to conceive that readers covering the majority of properly placed tags in a category can still receive tag responses even when they do not enforce all tags to respond. The energy cost can be therefore reduced if we design an MTP protocol accordingly.

B. ET-MTP Design

ET-MTP efficiently addresses the MTP problem in two stages, Energy- and Time-efficient MTD (*ET-MTD*) and PIC. Compared with T-MTD, ET-MTD aims to form the reader vector V more energy-efficiently. Reader cluster construction, misplaced-tag detection, and PIC follow the same processes as that of T-MTP. We only expatiate on how ET-MTD forms the reader vector V for the purpose of conciseness.

ET-MTD forms the reader vector V through two substeps in which ET-MTD forms reader vectors V_1 and V_2, respectively. In the first substep, readers are sequentially activated to broadcast a query message comprising a category ID c_k and a probability value p_k. Upon receiving the query message, tags in the category of c_k send a response with probability p_k. We define $p_k \in (0,1)$ to be

$$p_k = 1/n'_k, \quad (3)$$

where n'_k denotes the approximate number of inventory items in the category of c_k and those items are covered by a reader with transmission power level l. We estimate n'_k by $n'_k = \lceil V_l/V_k \rceil$, where V_l represents the volume of a reader's covering region at transmission power level l and V_k represents the volume of an inventory item of category c_k. It is easy to estimate V_l and V_k using the communication radius corresponding to l and the dimension information of inventory items, respectively. In the first substep, we only need 1-bit tag response to confirm a tag's presence. Regarding singleton and collision slots as *non-empty slots*, we form V_1 as

$$V_1[i] = \begin{cases} 0, & \text{if } r_i \text{ receives an empty slot} \\ 1, & \text{if } r_i \text{ receives a non-empty slot} \end{cases}$$

In the second substep, ET-MTD forms the reader vector V_2 through activating readers with $V_1[i] = 0$. The query message to be sent only contains c_k. Tags in the category of c_k must respond to the query message upon receiving it. A 10-bit random bitstring is sent as tag response for the purpose of distinguishing the slot state. Activating each reader with $V_i = 0$ for one time slot, we form the reader vector V_2 as

$$V_2[i] = \begin{cases} 0, & \text{if } V_1[i] \neq 0 \\ 0, 1, \text{or } 2, & \text{by Equation 2 if } V_1[i] = 0 \end{cases}$$

Finally, ET-MTD forms the reader vector V by $V[i] = V_1[i] + V_2[i]$. Using V, ET-MTP constructs reader clusters, detects misplaced tags, and conducts PIC for positioning misplaced tags exactly the same with T-MTP. The detection accuracy of ET-MTD is also similar to that of T-MTD, as discussed in Section IV-C.

C. Discussion of Energy Cost Reduction

We consider the scenario that a reader r_i covers n'_k tags and informs each tag to respond with probability p_k. The number of tag responses follows a binomial distribution when forming $V_1[i]$. When all or no tags respond, ET-MTP yields no energy cost reduction. If no tag responds when forming $V_1[i]$, all tags will be enforced to respond when forming $V_2[i]$. In this case ET-MTP degenerates into T-MTP. Otherwise, ET-MTP reduces energy cost through decreasing the number of tag responses. Specifically, we conclude the probability of reducing k' tag responses, denoted as $Pr(k' \mid p_k, n'_k)$, as follows:

$$Pr(k' \mid p_k, n'_k) = \begin{cases} p_k^{n'_k} + (1-p_k)^{n'_k}, & \text{if } k' = 0 \\ \binom{n'_k}{n'_k - k'} p_k^{n'_k - k'} (1-p_k)^{k'}, & \text{if } 0 < k' < n'_k \end{cases}$$

Substituting p_k by Equation 3, we derive the probability of ET-MTP reducing k' tag responses given n'_k tags covered, denoted as $Pr(k' \mid n'_k)$, as follows:

$$Pr(k' \mid n'_k) = \begin{cases} \frac{1}{{n'_k}^{n'_k}} + (1 - \frac{1}{n'_k})^{n'_k}, & \text{if } k' = 0 \\ \binom{n'_k}{n'_k - k'} \frac{1}{{n'_k}^{n'_k - k'}} (1 - \frac{1}{n'_k})^{k'}, & \text{if } 0 < k' < n'_k \end{cases}$$

Basically, it is highly probable to reduce $n'_k - 1$ tag responses. This is because $p_k n'_k = 1$ (by Equation 3) tag response has the highest probability given that the number of tag responses follows a binomial distribution.

D. Performance Analysis and Limitations

***Remark** 5:* The optimal number of tag responses N_{ET-MTP} and the optimal execution time T_{ET-MTP} for ET-MTP to pinpoint misplaced tags are as follows:

$$N_{ET-MTP} = \sum_{k=1}^{u} p_k n_k + \alpha h n,$$

$$T_{ET-MTP} = ((\sum_{k=1}^{u} \beta_k + u)m + \alpha h n) t_{cid} + (\sum_{k=1}^{u} \beta_k m + \alpha h n) t_{10b} + um(t_p + t_{1b}),$$

where n_k represents the number of tags in the category of c_k, β_k the percentage of readers with $V_1[i] = 0$ corresponding to the category of c_k, t_p the transmission time of p_k, and t_{1b} the transmission time of 1-bit tag response.

We derive Remark 5 as follows. First, to form V_1, the category ID and the probability value are contained in the query message and 1-bit tag response is used. Thus forming V_1 for all u categories costs $um(t_{cid} + t_p + t_{1b})$ time and at least $\sum_{k=1}^{u} p_k n_k$ tag responses. Second, to form V_2, only readers with $V_1[i] = 0$ broadcast query messages containing the category ID and 10-bit tag response is used. Then forming V_2 for all u categories induces $\sum_{k=1}^{u} \beta_k m(t_{cid} + t_{10b})$ time cost and at least αn tag responses. Finally, PIC costs at least $\alpha h n(t_{cid} + t_{10b})$ time and $\alpha(h-1)n$ tag responses, as we discussed in the analysis of Remark 4. N_{ET-MTD} and T_{ET-MTD} claimed in Remark 5 can therefore be derived through summing up related cost in the above three parts.

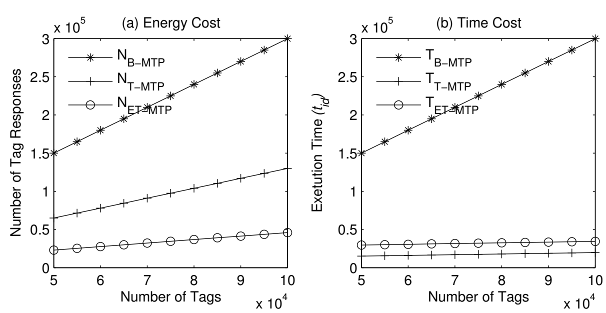

Fig. 5. Performance comparison of B-MTP, T-MTP, and ET-MTP.

Figure 5 plots the optimal performances of B-MTP, T-MTP, and ET-MTP under the scenario where $m = 50$, $k = 1000$,

$h = 3$, $\alpha = 0.15$, 96-bit tag ID, and 7-bit p_k. The transmission time t_p and t_{1b} are approximately estimated by $7t_{id}/96$ and $t_{id}/96$, respectively. Suppose that a reader can cover at least 100 tags. Then $p_k = 1/n'_k \leq 0.01$. For simplicity, we use $p_k = 0.01$ and $\sum_{k=1}^{u} p_k n_k = 0.01 \sum_{k=1}^{u} n_k = 0.01n$ for N_{ET-MTP}, and use u instead of $\sum_{k=1}^{u} \beta_k \leq u$ for T_{ET-MTP}. As we expect, ET-MTP further decreases the number of tag responses than T-MTP as shown in Figure 5(a). A limitation of ET-MTP is that two rounds of reader activation for forming the reader vector V cost more time than T-MTP, as shown in Figure 5(b).

In summary, it depends on which of time efficiency and energy efficiency is concerned more when we choose between T-MTP and ET-MTP. If timely MTP is desired, we prefer T-MTP. If active tags are used and energy saving is desired, we prefer ET-TMP that yields higher energy efficiency than T-MTP does with competitive time efficiency. Hybrid protocol design by adaptively switching between them toward the optimal performance is also worthy of consideration.

VI. Simulation Evaluation

This section evaluates the efficiency of B-MTP, T-MTP, and ET-MTP by simulations. We compare our protocols with the-state-of-the-art RPCV [8]. Two performance metrics, including the execution time and the number of tag responses, are used to evaluate time efficiency and energy efficiency, respectively. We average the results over 100 trials.

A. Environment Configuration

We simulate the system as follows. The number of readers and the number of tag categories are $m = 50$ and $u = 1000$, respectively. The number of tags n varies from 50000 to 100000 with n/u per category. The readers are deployed in grid on the ceiling of the simulated system. The number of reference readers for tag positioning by Equation 1 is set to $h = 3$. Each reader has 38 tunable transmission power levels as the representative RFID positioning scheme in [16]. Each tag has a 96-bit unique ID. The transmission time of the tag ID (i.e., t_{id}), is used as time unit. The transmission time of s bits is estimated by $st_{id}/96$. The transmission time of the category ID is therefore $t_{cid} = \lceil \log_2 u \rceil t_{id}/96 = 10t_{id}/96$. Following the system configuration of RPCV, all inventory items are with the same volume. In this case, each reader covers on average $1000 \leq n/m \leq 2000$ tags and 12 bits is enough to express the probability $p_k = m/n$ by Equation 3. Then the transmission time of p_k can be estimated by $12t_{id}/96$.

In RPCV simulation [8], each tag needs to be identified dozens of times for RPCV to find misplaced tags. To conduct an objective comparison, we consider RPCV with each tag being identified 10 times. Both RPCV and our protocols sequentially activate readers to collect information in the simulation. Thus, we can derive a lower bound of the number of tag responses and the execution time of RPCV, denoted as N_{RPCV} and T_{RPCV}, respectively, as follows:

$$N_{RPCV} = 10n, \; T_{RPCV} = 10nt_{id}. \tag{4}$$

We hereby compare analyzed optimal performances of RPCV and our protocols in Figure 6 to indicate their efficiency potential. Both time cost and energy cost corresponding to the lower bound of RPCV are far beyond that of our protocols. Thus, we directly use the lower bound in Equation 4 for comparisons. Similarly, we use the lower bound of B-MTP in Remark 1 for the comparison, for B-MTP is neither a wise choice for an efficient MTP solution.

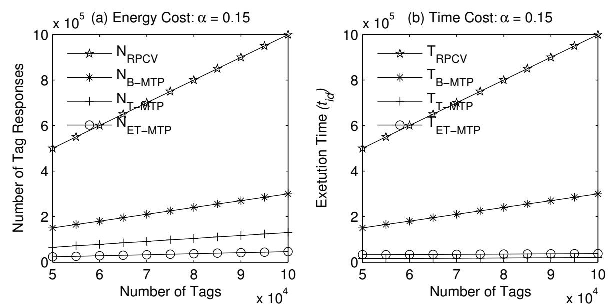

Fig. 6. Analytical performance comparison of RPCV, B-MTP, T-MTP, and ET-MTP.

B. Time Efficiency and Energy Efficiency

We evaluate the performance of proposed protocols with varying number of tags n and misplacement ratio α. In each scenario, αn tags are randomly picked and then are randomly placed away from the area where they are supposed to be. These tags are therefore the misplaced tags to be pinpointed. Note that we deliberately distribute misplaced tags distant further than the threshold (i.e., $2d_r$, see Section IV-C) to avoid false negatives, because we are interested mainly in time efficiency and energy efficiency in this paper.

Figure 7 reports the results under various scenarios in comparison with RPCV. As expected, all our protocols, namely B-MTP, T-MTP, and ET-MTP, outperform RPCV in both time-efficiency and energy efficiency. Among our protocols, T-MTP yields the highest time efficiency while ET-MTP yields the highest energy efficiency. Both T-MTP and ET-MTP are more time-efficient and energy-efficient than is B-MTP. When $\alpha = 0.05$ as shown in Figure 7(a)-(b), compared with RPCV, T-MTP can averagely increase the time efficiency by up to 93%, and ET-MTP can averagely increase the energy efficiency by up to 95%. While the time efficiency improvement and the energy efficiency improvement when $\alpha = 0.15$ can still be as much as 90% (Figure 7(f)) and 91% (Figure 7(e)), respectively.

In summary, our efficient MTP protocols, say T-MTP and ET-MTP, can increase both time efficiency and energy efficiency by over 70%, when compared with RPCV [8]. This is because T-MTP and ET-MTP are more efficient than B-MTP which requires 70% lower time and energy cost in the simulation (by Remark 1 and Equation 4).

C. Further Discussion of Parallel Reading

We have evaluated protocol efficiency with readers following sequential reading. It is not hard to infer that time efficiency will be further improved if we allow multiple readers reading in parallel while the number of tag responses will not

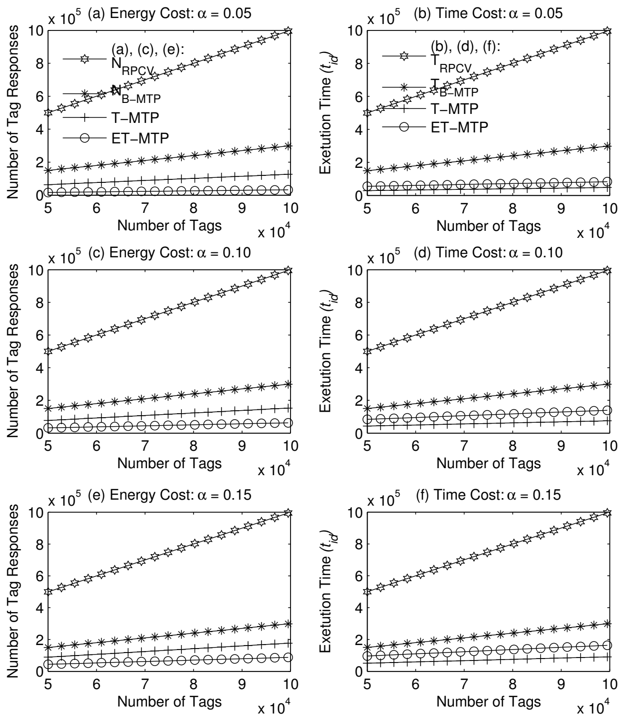

Fig. 7. Performance comparison of RPCV, B-MTP, T-MTP, and ET-MTP with varying tag number n and misplacement ratio α.

be affected too much. Without considering the reader collision problem [18], time lower bounds for m readers collecting n tag IDs with sequential and parallel reading are nt_{id} and nt_{id}/m, respectively. Figure 8 plots the lower bound with varying m and n. Parallel reading provides a promising chance of time efficiency improvement as shown in Figure 8.

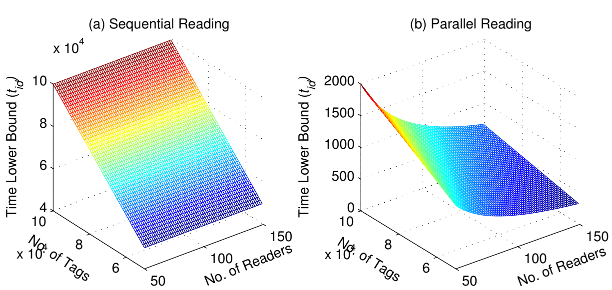

Fig. 8. Analytical performance comparison of sequential and parallel reading.

VII. Conclusion

Misplacement errors keep being a major concern in production economics due to their serious impact on profit. Departing from previous research that needs to process a large amount of data, this paper investigates efficient MTP solutions from the perspective of communication protocol design. We propose T-MTP that detects misplaced tags based on reader vectors instead of tag vectors. T-MTP yields significantly increased time efficiency as well as energy efficiency than basic solutions requiring tag-wise positioning. Considering applications to employ more and more popular active tags with self-equipped batteries, we further propose ET-MTP. ET-MTP addresses the MTP problem through requiring responses from only partial tags in favor of energy saving. Analysis and experiments demonstrate that the proposed protocols outperform the state of the art in both time efficiency and energy efficiency, which are important to guarantee protocol scalability in large RFID systems.

Acknowledgment

This work is partially supported by HK PolyU G-U810.

References

[1] D. Delen, B. Hardgrave, and R. Sharda, “RFID for better supply-chain management through enhanced information visibility,” *Production and Operations Management*, vol. 16, no. 5, pp. 613–624, 2007.
[2] D. Zhang, J. Ma, Q. Chen, and L. Ni, “An RF-based system for tracking transceiver-free objects,” in *IEEE PerCom*, 2007, pp. 135–144.
[3] V. Wu and N. Vaidya, “RFID trees: A distributed RFID tag storage infrastructure for forest search and rescue,” in *IEEE SECON*, 2010, pp. 1–8.
[4] C. Qian, H. Ngan, and Y. Liu, “Cardinality estimation for large-scale RFID systems,” in *IEEE PerCom*, 2008, pp. 30–39.
[5] T. Li, S. Wu, S. Chen, and M. Yang, “Energy efficient algorithms for the RFID estimation problem,” in *IEEE INFOCOM*, 2010, pp. 1–9.
[6] B. Sheng, C. Tan, Q. Li, and W. Mao, “Finding popular categories for RFID tags,” in *ACM MobiHoc*, 2008, pp. 159–168.
[7] T. Li, S. Chen, and Y. Ling, “Identifying the missing tags in a large RFID system,” in *ACM MobiHoc*, 2010, pp. 1–10.
[8] L. Ferreira Chaves, E. Buchmann, and K. Böhm, “Finding misplaced items in retail by clustering RFID data,” in *ACM EDBT*, 2010, pp. 501–512.
[9] D. Huang and H. Kapoor, “Towards lightweight secure communication protocols for passive RFIDs,” in *IEEE SECON*, 2009, pp. 1–9.
[10] A. Raman, N. DeHoratius, and T. Zeynep, “Execution: The missing link in retail operations,” *California Management Review*, vol. 43, no. 3, pp. 136–152, 2001.
[11] W. Bishop, “Documenting the value of merchandising,” National Association for Retail Merchandising Service, Tech. Rep., 2003.
[12] Y. Rekik, E. Sahin, and Y. Dallery, “Analysis of the impact of the RFID technology on reducing product misplacement errors at retail stores,” *International Journal of Production Economics*, vol. 112, no. 1, pp. 264–278, 2008.
[13] C. Qian, Y. Liu, H. Ngan, and L. Ni, “ASAP: scalable identification and counting for contactless RFID systems,” in *IEEE ICDCS*, 2010, pp. 52–61.
[14] S. Chen, M. Zhang, and B. Xiao, “Efficient information collection protocols for sensor-augmented RFID networks,” in *IEEE INFOCOM*, 2011, pp. 1–9.
[15] A. Matic, A. Papliatseyeu, V. Osmani, and O. Mayora-Ibarra, “Tuning to your position: FM radio based indoor localization with spontaneous recalibration,” in *IEEE PerCom*, 2010, pp. 153–161.
[16] C. Wang, H. Wu, and N. Tzeng, “RFID-based 3-D positioning schemes,” in *IEEE INFOCOM*, 2007, pp. 1235–1243.
[17] IDENTEC SOLUTIONS, http://www.identecsolutions.com/.
[18] Z. Zhou, H. Gupta, S. Das, and X. Zhu, “Slotted scheduled tag access in multi-reader RFID systems,” in *IEEE ICNP*, 2007, pp. 61–70.
[19] B. Hendrickson, “Conditions for unique graph realizations,” *SIAM Journal of Computing*, vol. 21, pp. 65–84, 1992.
[20] B. Sheng, Q. Li, and W. Mao, “Efficient continuous scanning in RFID systems,” in *IEEE INFOCOM*, 2010, pp. 1–9.
[21] M. Zhang, T. Li, S. Chen, and B. Li, “Using analog network coding to improve the RFID reading throughput,” in *IEEE ICDCS*, 2010, pp. 547–556.
[22] S. Lee, S. Joo, and C. Lee, “An enhanced dynamic framed slotted ALOHA algorithm for RFID tag identification,” in *IEEE MobiQuitous*, 2005, pp. 166–172.
[23] J. Myung and W. Lee, “Adaptive splitting protocols for RFID tag collision arbitration,” in *ACM MobiHoc*, 2006, pp. 202–213.
[24] V. Namboodiri and L. Gao, “Energy-aware tag anti-collision protocols for rfid systems,” in *IEEE PerCom*, 2007, pp. 23–36.
[25] Philips ICode system design guide, http://www.nxp.com/.
[26] EPC class-1 generation-2 RFID protocol V.1.0.9, http://www.epcglobalinc.org/home.