Efficient Misplaced-Tag Pinpointing in Large RFID Systems

Kai Bu, Bin Xiao, *Senior Member*, *IEEE*, Qingjun Xiao, and Shigang Chen, *Member*, *IEEE*

Abstract—Radio-Frequency Identification (RFID) technology brings many innovative applications. Of great importance to RFID applications in production economics is misplaced-tag pinpointing (MTP), because misplacement errors fail optimal inventory placement and thus significantly decrease profit. The existing MTP solution [1], originally proposed from a data-processing perspective, collects and processes a large amount of data. It suffers from time inefficiency (and energy-inefficiency as well if active tags are in use). The problem of finding efficient solutions for the MTP problem from the communication protocol design perspective has never been investigated before. In this paper, we propose a series of protocols toward efficient MTP solutions in large RFID systems. The proposed protocols detect misplaced tags using reader positions instead of tag positions to guarantee the efficiency and scalability as system scale grows, because RFID readers are much fewer than tags. Considering applications that employ active tags, we further propose a solution requiring responses from only a subset of tags in favor of energy saving. We also design a distributed protocol that enables each reader to independently detect misplaced tags. We then investigate how to apply the proposed protocols in scenarios with tag mobility. To evaluate the proposed protocols, we analyze their optimal performances to demonstrate their efficiency potential and also conduct extensive simulation experiments. The results show that the proposed protocols can significantly increase the time efficiency and the energy efficiency by over 70 percent on average when compared with the best existing work.

Index Terms—RFID, misplaced-tag pinpointing, time-efficient, energy-efficient, distributed protocol

1 Introduction

Radio-frequency Identification (RFID) technology stimulates innovative applications in various fields, such as supply chain management [2] and target tracking [3], [4]. To support these applications, researchers dedicate significant effort to addressing important problems in RFID systems. Such problems include tag identification [5], [6], [7], [8], cardinality estimation [9], [10], [11], finding popular categories [12], missing-tag detection and identification [13], [14], [15], and misplaced-tag pinpointing (MTP) [1]. In this paper, we concentrate on one of these important problems, *MTP* in large RFID systems.

The MTP problem aims to detect and pinpoint tags attached to misplaced inventory items in a large warehouse, retailing store, wharf, or airport. The misplacement error is a notorious foe against optimal inventory placement. Optimal placement can increase profit by up to 8.1 percent [16]. Such an increase would yield $1.1 billion more profit for Wal-Mart, the world's largest retailer [1]. Misplacement errors, however, hinder us from enjoying this benefit. The statistics in [17] show that on average consumers of a leading retailer cannot find 16 percent of inventory items in the stores because those items are misplaced. Furthermore, Hong Kong International Airport, one of the largest airports in the world, loses more than $20 million annually to relocate misplaced and mistransported bags [7]. Countermeasures against misplacement errors, therefore, represent one of the primary concerns in production economics. Rekik et al. suggest that the RFID technology can be adopted to reduce inventory misplacement errors [18]. One significant application is thus to pinpoint misplaced tags and in return to pinpoint their tagged misplaced inventory items for the purpose of replacement.

The recent solution for MTP is a database-oriented method called RPCV [1]. In RPCV, one reader controls many antennas, each of which is located at one position. RPCV requires inventory items to be placed exactly following a layout plan and uses tag vectors to represent tags attached to inventory items. A tag vector includes the number of readings by the right antenna (i.e., whose corresponding position covers where the tagged item should be placed) and by wrong ones. RPCV finds misplaced tags by processing and classifying all tag vectors. The design of RPCV primarily focuses on computational efficiency, whereas it is not concerned with communication efficiency, that is, how fast the information from tags can be collected in order to construct tag vectors and how much energy the tags have to spend in the collection process. In fact, information collection from all tags in a large RFID system is very time consuming [7], [19]. Time efficiency may outweigh computational efficiency. In addition, when battery-powered active tags are used, energy efficiency becomes important. RPCV requires each tag to respond dozens of times for finding misplaced items whereas too many tag responses cost active tags a lot of energy [10], [20]. Another limitation of RPCV is its dependence on layout

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plans. Practically, it is laborious and challenging to place inventory items exactly in accordance with layout plans.

Unlike RPCV's focus on data processing, this paper studies the MTP problem from a new angle—the communication protocol design perspective. Particularly, we design efficient communication protocols that collect information from tags to readers for detecting and pinpointing misplaced tags. In order to achieve time efficiency and energy efficiency, we have to abandon the basic approaches in RPCV [1], including its underlying tag vectors, and replace them with reader vectors, which take much less time to collect. To save energy, we randomly select only a subset of tags to respond each time when reader vectors are constructed, which compares favorably with RPCV where every tag has to transmit many times. Our protocols do not require tagged items to be placed strictly based on a predetermined layout plan. To make it more efficient and robust, we further propose a distributed solution that enables each reader to independently detect misplaced tags. We also discuss how to handle scenarios with tag mobility.

In summary, this paper makes the following contributions to efficient MTP solution in large RFID systems.

- Investigate Basic MTP protocols (*B-MTP*) based on tag-wise positioning and propose a heuristic reader activation method to accelerate MTP protocols. B-MTP collects less information for tag positioning than RPCV collects for forming tag vectors. Yet the performance analysis of B-MTP demonstrates its inefficiency and unscalability in large RFID systems.
- Propose a time-efficient MTP protocol (*T-MTP*) 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 also has better energy efficiency in comparison with B-MTP.
- Propose an Energy-Time-efficient MTP protocol (*ET-MTP*) to further enhance energy efficiency of T-MTP by requiring only a subset of tags to send responses.
- Validate the performance of proposed protocols through extensive analysis and simulation. The results show that the proposed protocols can significantly outperform RPCV [1] for improving time efficiency and energy efficiency by over 70 percent on average.
- Improve on [21] by proposing a Distributed MTP protocol (*D-MTP*), a distributed protocol that enables each reader to independently detect misplaced tags within its coverage. Our analysis shows that D-MTP is more time-efficient than T-MTP and more energy efficient than ET-MTP in some cases.
- Investigate how to distinguish mobile tags from misplaced tags using multiround misplaced-tag detection results.

The rest of this paper is organized as follows: Section 2 defines the problem and the system. Section 3 discusses B-MTP and indicates its limitations through performance analysis. Sections 4 and 5 present T-MTP and ET-MTP toward high time efficiency and high energy efficiency, respectively. Section 6 reports the simulation results. Section 7 discusses D-MTP, a distributed MTP protocol that enables each reader to independently detect misplaced tags. Section 8 discusses tag mobility and channel reliability. Finally, Section 9 concludes the paper and indicates the future work.

2 System Model

2.1 Problem Overview

Consider a large RFID system that consists of a set of readers $R = \{r_1, \dots, r_i, \dots, r_m\}$ and a set of tags $T = \{t_1, \dots, t_j, \dots, t_n\}$. The readers are deployed at known positions to provide position reference for positioning tags [22]. We also call them *reference readers*. The tags could be either passive or active according to specific system requirements. Each tag has a unique ID and attaches to an inventory item. (Hereafter in this paper, we use terms *inventory item* and *tag* interchangeably.) Predefined bit positions on the ID of each tag specify various kinds of information about the inventory item [23]. In particular, one section of the tag ID, called *category ID*, specifies the category of the inventory item attached with the tag [12], [23]. The set of distinct category IDs is denoted as $C = \{c_1, \dots, c_k, \dots, c_u\}$. Inventory items are placed by categories—a category of inventory items should be properly placed together in a certain area. But we do not require inventory placement to strictly follow any layout plan, which, however, is a necessary assumption for RPCV [1].

In such an RFID system, we formulate the MTP problem as follows: We denote by A_k the area where tags in the category of c_k are placed. If a tag of category c_k locates away from A_k, we regard it as misplaced.[1] The MTP problem is to pinpoint misplaced tags. Once misplaced tags are pinpointed, one can directly walk toward or use navigation methods (e.g., [24]) to approach them for replacement. We observe that in practice, although some tags could be misplaced, a majority of tags in each category are still properly placed. This observation provides valuable hints on detecting misplaced tags without using tag positions (Sections 4, 5, 7, and 8.1).

2.2 Assumptions and Justifications

In this paper, we concentrate on scenarios not that complicated but general enough to acquire insights for efficient MTP solutions. Several reasonable assumptions we make are as follows:

We assume that an inventory item list in accordance with all present items is maintained on a back-end server that executes the MTP protocol and communicates with the readers. The list is updated whenever new items move into the system or existing items move out. Considering that tags may be stolen by misbehaving workers or customers, we can adopt missing-tag detection and identification methods [13], [14], [15] to timely detect and identify the missing tags. The records corresponding to identified missing tags should be immediately deleted from the list.

1. The exact location of A_k is not predetermined based on a layout plan. Instead, it is simply where the tags in c_k happen to be. If most tags in c_k are there while one tag is moved to another location, then that tag is misplaced (away from others in the same category).

To locate tags, we assume that the representative RFID positioning scheme in [22] is adopted. In this scheme, a reader has a set of transmission power levels [25]. The communication radius corresponding to a power level can be obtained by a set of reference tags deployed at known positions [22] or an RF site survey using a positioning device and radio signal strength measurement device [26]. Without loss of generality, we consider scenarios where readers are deployed on the ceiling of the system, so that communications with tags are relatively free of obstacle. To locate a tag, we need its distance measurements to at least $h \geq 3$ reference readers. Note that theoretically it requires distance measurements to at least four reference readers to locate a tag in 3D space [27]. Combining the implicit constraint that a tag cannot locate higher than the height of the system, $h = 3$ however is the least requirement for the basic positioning scenario in [22].

For now, we consider only scenarios where 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 [26]. 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 the 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 [26], it is still very challenging to achieve this with readers frequently adjusting transmission power levels for tag positioning [22]. But we can easily apply our MTP protocols to parallel reading scenarios once a more sophisticated reader scheduling protocol is available. We will discuss time efficiency gains by parallel reading in Section 6.4.

Second, when mobile tags exist, being away from the supposed area cannot verify a misplaced tag. We need to further verify whether the tag is carried by moving machines or wandering customers. To sidestep this problem, we first investigate efficient MTP protocols with all tags being stationary (Sections 3, 4, 5, 6, and 7) and then discuss how we can apply them to scenarios with mobile tags (Section 8.1).

2.3 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.

First, time efficiency—measured based on protocol execution time—is highly important for an MTP protocol to be scalable as RFID systems grow large. Time efficiency is a primary concern for almost all prior RFID work, such as tag identification [5], [6], [7], [8], cardinality estimation [9], [10], [11], and missing-tag detection and identification [13], [14], [15].

Second, energy efficiency is measured by the number of tag responses during protocol execution. An energy-efficient MTP protocol is essential in an RFID system with many active tags. Active tags can significantly impulse the growth of RFID applications because of their ability of initiating communication and their hundreds-of-feet communication radius, which is much longer than that of passive tags. However, active tags depend on self-carried batteries to enable any operation. Thus, enjoying the improved system performance brought by active tags, we should make the energy cost as low as possible by controlling the number of tag responses [10], [20].

3 Preliminary and Basic MTP Protocols

This section discusses B-MTP based on tag-wise positioning, which locates each tag. We analyze its performance and limitations, indicating the demand for more efficient MTP protocols in large RFID systems.

3.1 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 therefore misplaced ones and should be replaced.

Based on the above intuition, we investigate two B-MTP designs, 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.

3.1.1 IPB-MTP Design

IPB-MTP locates tags in n rounds, each of which is dedicated to locating one of n 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. The round for a tag ends when h readers are identified to cover the tag and each of the h readers has determined the minimum transmission power level l_{min} for it to cover the tag. Recall that h is the number of reference readers it needs to locate a 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 [22]. Let (x_{ri}, y_{ri}, z_{ri}) denote 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. The representative RFID positioning scheme in [22] estimates the position of t_j as follows:

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

Its best performance can limit the position error to less than 5 percent of the longest edge of the system [22].

To speed up MTP protocols, we can activate readers in an optimized order rather than always following the ordering defined in the set R. The heuristic stems from the truth that if a reader r_i covers a tag t_j (i.e., r_i and t_j can communicate with each other), then

- readers near to r_i are more likely to cover t_j than those far from r_i;
- 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.

Hence, after we find a reader r_i that covers a tag t_j, we activate the remaining readers in ascending order of their distances to r_i. In a subsequent round for another tag t_k that belongs to the same category of t_j, we will activate r_i first and then activate other readers in the ascending order of their distances to r_i.

3.1.2 CAB-MTP Design

There are different ways to collect information about which readers cover which tags. In IPB-MTP, we iterate through tags. For each tag, readers take turn to broadcast the tag ID to see if they cover the tag. Alternatively, we can iterate through readers. For each reader, it performs a tag-identification protocol [5], [6], [7], [8] to identify the IDs of the tags within its coverage. This leads to our second protocol, CAB-MTP, which differs from IPB-MTP only in its way of collecting information about which readers cover each tag. The rest of the protocol is the same.

There are two types of tag-identification protocols, based on slotted Aloha [5], [28], [29] and tree traversal [6], [30], respectively. We design CAB-MTP using slotted Aloha because it can yield higher efficiency in large systems than can Tree-traversal [7]. We hereby briefly review the basics of slotted Aloha-based collision arbitration protocols to keep the paper self-contained and refer interested readers to [5], [28], [29] for more details. 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 [9]. The reader can correctly receive the tag response only in a singleton slot; the reader has to continuously send new frames with adjusted frame size until no collision occurs.

3.2 Performance Analysis and Limitations

We first derive a performance lower bound for B-MTP and then analyze the optimal performances of IPB-MTP and CAB-MTP to indicate how close they can approach the lower bound.

Remark 1. A lower bound on 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, even though such additional time is very small when compared with t_{id}. (We omit this additional time cost in the analysis.) Second, it also incurs additional overhead when reference readers further communicate with the to-be-located tag to determine l_{min}.

We will analyze the optimal performances of IPB-MTP and CAB-MTP by Remark 2 and Remark 3, respectively, indicating 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 covering a to-be-located tag 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 is $2hnt_{id}$. 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: 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. Because the highest efficiency of slotted Aloha is $\frac{1}{e}$ (i.e., optimally $\frac{1}{e}$ of the tags can be identified within one query frame, where e is the natural constant) [7], [19], it takes r_i at least $en_{ri}t_{id}$ time to identify n_{ri} tags. Then, the optimal execution time is derived by

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

The first line uses $\sum_{i=1}^{m} n_{ri} \geq hn$, which is deduced from the condition that each tag is covered by at least h readers. Furthermore, because all unread tags should respond to the query message and optimally $1-\frac{1}{e}$ of them will continue to respond to the following query message, we can derive the optimal number of tag responses as follows:

$$\sum_{i=1}^{m}\left(n_{ri} + \left(1-\frac{1}{e}\right)n_{ri} + \left(1-\frac{1}{e}\right)^2 n_{ri} + \cdots\right)$$
$$\approx \sum_{i=1}^{m} en_{ri} \geq ehn.$$

The second derivation again uses $\sum_{i=1}^{m} n_{ri} \geq hn$.

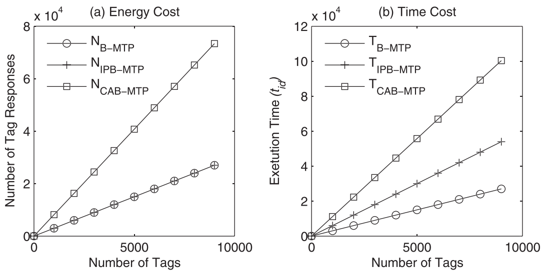

Fig. 1. Performance comparison of B-MTP, IPB-MTP, and CAB-MTP.

Fig. 1 summarizes the performance of B-MTP designs in Remarks 1, 2, and 3, under the basic scenario where $h = 3$. 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 size (i.e., the number of tags in an RFID system). This limitation not only hinders protocol efficiency but also decreases protocol scalability for large RFID systems. Next, we will present two more efficient MTP protocols toward increasing time efficiency and energy efficiency, respectively.

4 T-MTP: Time-Efficient Misplaced-Tag Pinpointing Protocol

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

4.1 Motivation

Reader positions rather than tag positions can also be used to detect misplaced tags. Fig. 2 illustrates the intuition under a scenario with uniformly deployed readers. 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 left cluster, which has a much larger cluster size (i.e., the number of included readers) than does the right one. The tag covered by readers in the right smaller cluster is therefore detected as misplaced tags and needs to be located for replacement.

If the category is compactly stored in a small place, only a few nearby readers cover it. They will form a small cluster that is similar to the one for a single misplaced tag. In this case, we can easily detect misplaced tags by estimating the number of tags under either reader cluster. But in a large RFID system a category of tags usually spreads in a large area covered by many readers. Such RFID systems are of our interest in this paper.

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

4.2 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 whether 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 empty or not. Second, because we no longer require tag-wise positioning, tag IDs are unnecessary to be included in responses. Indices for distinguishing 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 [31], 10 bits, which is much shorter than the length of tag ID (usually 96 bits [23]), is enough to verify a collision [9].

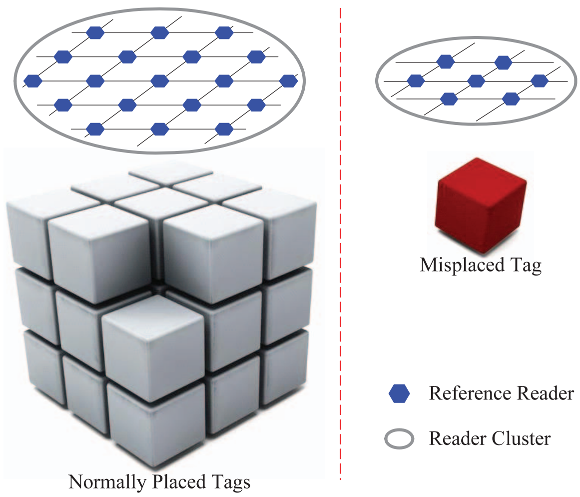

Fig. 2. Misplaced-tag detection using reader clusters. The tag covered by readers in the right smaller cluster is misplaced away from those covered by readers in the left larger cluster.

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

4.2.1 Stage I: T-MTD

To detect misplaced tags in a category c_k, T-MTD sequentially activates each reader for one time slot to determine whether it covers tags of category c_k, with all readers using a same transmission power level. 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 by transmitting a 10-bit random bitstring with error-detection (e.g., CRC) embedded. 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 *reader vector* V with the element $V[i]$ defined by

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

Based on the reader vector V, T-MTD detects misplaced tags through constructing *reader clusters*. A reader cluster consists of neighboring readers with $V[i] \neq 0$ surrounded by readers with $V[i] = 0$. Fig. 3 illustrates reader cluster construction. The number of readers in a reader cluster indicates the cluster size. Intuitively, the largest reader

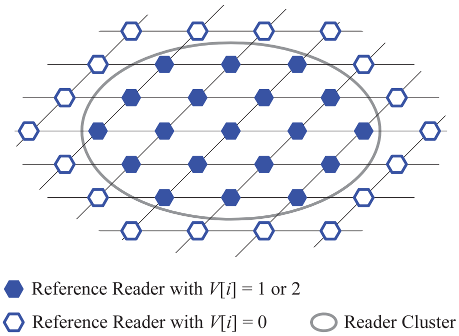

Fig. 3. Reader cluster construction using the reader vector V.

cluster covers properly placed tags because a majority of tags in a category are supposed to be placed in the right area (Section 2.1). Tags covered by readers in other smaller reader clusters are separated away from the right area and therefore are detected as misplaced ones.

4.2.2 Stage II: PIC

PIC further activates readers to collect enough information for positioning misplaced tags, which are detected in stage I. By (1), the to-be-collected information is distance measurements between each misplaced tag and at least h reference readers. The active reference reader broadcasts a query message containing category ID c_k by gradually tuning the transmission power level until it determines l_{min}. The communication radius corresponding to l_{min} is used as the distance measurement. Whether a reader covers one or multiple misplaced tags can be determined using the slot states of singleton or 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 (Section 3.1) for accelerating PIC.

4.3 Discussion of Misplaced-Tag Detection Accuracy

T-MTD has no false positives but false negatives. T-MTD is false positive free because some misplaced tags must exist if multiple reader clusters exist. Otherwise, if only one reader cluster is constructed, T-MTD reports no misplaced tags. T-MTD, however, may return false negatives if misplaced tags are not far away from the supposed area beyond a distance threshold. Specifically, we deduce that 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:

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

4.4 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:

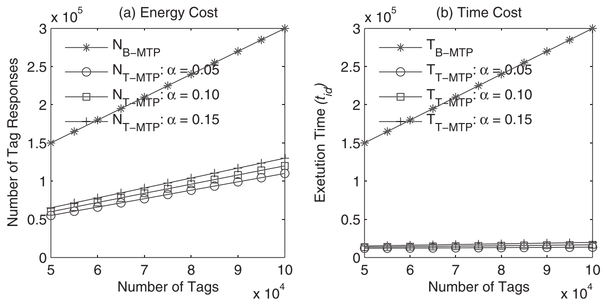

Fig. 4. Performance comparison of B-MTP and T-MTP.

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

where t_{cid} denotes the transmission time of the category ID, t_{10b} the transmission time of a 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;
- 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 induces 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 to form the reader vector V, we therefore derive N_{T-MTP} and T_{T-MTP} in Remark 4.

Fig. 4 plots the optimal performance of T-MTP under the scenario where $m = 50$, $u = 1{,}000$, $h = 3$, 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, Fig. 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 in use. The transmission time t_{cid} and t_{10b} can be approximately represented by $\frac{10}{96} t_{id}$ and $\frac{10}{96} t_{id}$, respectively. As shown in Fig. 4b, compared with B-MTP, 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. Furthermore, T-MTP also outperforms B-MTP in higher energy efficiency because of fewer tag responses as shown in Fig. 4a.

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

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

T-MTP 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 and within the reader's coverage will respond upon receiving the query message. Two or more tag responses, however, make no difference to distinguish a collision slot. We will

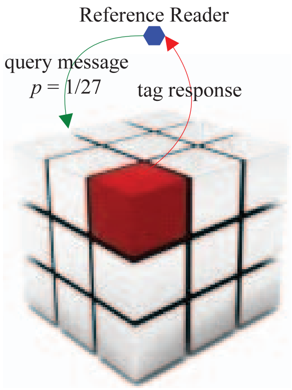

Fig. 5. One tag response expected with 27 tags responding with probability $p = \frac{1}{27}$.

present a more energy-efficient MTP protocol against this limitation.

5 ET-MTP: Energy-Time-Efficient Misplaced-Tag Pinpointing Protocol

This section presents ET-MTP, which further enhances 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.

5.1 Motivation

If a reader covering n' tags broadcasts a query message and each tag responds with probability p, we can expect pn' tag responses [10]. Fig. 5 illustrates an example scenario where $n' = 27$ and $p = \frac{1}{27}$. The reader is therefore likely to receive only one tag response ($n'p = 27 \times \frac{1}{27} = 1$). Similarly, when a reader receives a tag response, we can expect $\frac{1}{p}$ 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 if not all tags respond. The energy cost can be therefore reduced if we design an MTP protocol accordingly.

5.2 ET-MTP Design

ET-MTP efficiently addresses the MTP problem in two stages, Energy-Time-efficient MTD (*ET-MTD*) and PIC. Compared with T-MTD, ET-MTD forms the reader vector V more energy efficiently. Reader cluster construction, misplaced-tag detection, and PIC follow the same processes as that of T-MTP. Next, 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

$$p_k = \frac{1}{n'_k}, \tag{3}$$

where n'_k denotes the approximate number of inventory items that are in the category of c_k and are covered by a reader with transmission power level l. We estimate n'_k by $n'_k = \lceil \frac{V_l}{V_k} \rceil$, 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 time slots in which a reader receives responses as *nonempty slots*, we form V_1 as

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

Since we form V_1 with tags responding with probability p_k, chances are that some readers with $V_1[i] = 0$ cover tags in the category of c_k but receive no tag response. To avoid this issue, we further introduce the second substep.

In the second substep, ET-MTD forms the reader vector V_2 through activating readers with $V_1[i] = 0$. Each active reader sends a query message comprising only 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

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

Finally, ET-MTD forms the reader vector V by $V[i] = V_1[i] + V_2[i]$—the same reader vector as T-MTD forms by (2). 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 4.3.

5.3 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 $Pr(k'|p_k, n'_k)$, as follows:

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

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

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

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

Another common approach to conserving energy for active tags is *sleep scheduling* [32], [33]. Sleep scheduling aims to switch wireless nodes between sleep mode and active mode such that a wireless node keeps in sleep mode as often as possible. The rationale of sleep scheduling is that being active and listening to (or receiving) queries from readers consume energy, while such energy consumption can be conserved if a wireless node switches to sleep mode. However, it is quite challenging to determine the optimal length of sleep period that can minimize energy consumption yet cannot indulge any sleeping wireless node in application performance deterioration [32], [33]. In, for example, the MTP problem of our concern, it is hard for an MTP protocol to quickly detect misplaced tags that are in the sleep mode.

We choose to detect misplaced tags with all tags in active mode and conserve energy of active tags in two ways. First, we build ET-MTP on top of T-MTP, which is more time efficient than B-MTP. Through reducing the execution time, we shorten the time for each tag to listen to (or receive) queries from readers; such shortened time in return reduces energy consumption of active tags. Second, we design ET-MTP in such a way that it enforces only a subset of tags to respond. Since it is well known that transmitting packets costs wireless nodes more energy than listening to (or receiving) queries, we can harvest a significant energy efficiency gain by suppressing a large number of packets, namely tag responses [10], [20].

5.4 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:

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

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

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 wait for 10-bit tag responses. Thus, 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 (Section 4.4). Therefore, we can derive N_{ET-MTD} and T_{ET-MTD} claimed in Remark 5 through combining related cost in the above three parts.

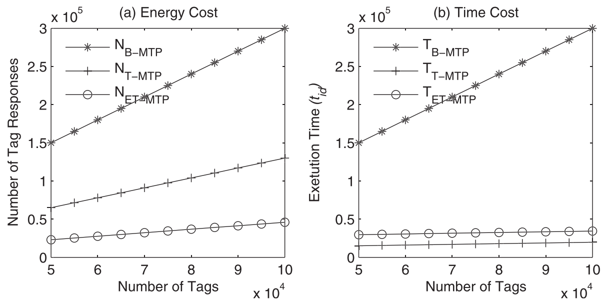

Fig. 6. Performance comparison of B-MTP, T-MTP, and ET-MTP.

Fig. 6 plots the optimal performances of B-MTP, T-MTP, and ET-MTP under the scenario where $m = 50$, $k = 1{,}000$, $h = 3$, $\alpha = 0.15$, 96-bit tag ID, and 7-bit p_k. The transmission time t_p and t_{1b} are approximately estimated by $\frac{7}{96} t_{id}$ and $\frac{1}{96} t_{id}$, respectively. Suppose that a reader can cover at least 100 tags. Then, $p_k = \frac{1}{n'_k} \leq 0.01$. 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 expected, ET-MTP induces fewer tag responses than does T-MTP as shown in Fig. 6a. A limitation of ET-MTP is that two rounds of reader activation for forming the reader vector V takes more time than does T-MTP, as shown in Fig. 6b.

In summary, it depends on which of time efficiency and energy efficiency is more significant 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 does T-MTP with competitive time efficiency. A hybrid protocol design by adaptively switching between them toward the optimal performance is also worthy of consideration.

6 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 [1]. We use two performance metrics, the execution time and the number of tag responses (Section 2.3), to evaluate time efficiency and energy efficiency, respectively. We average the results over 100 trials.

6.1 Environment Configuration

We simulate the system as follows: The number of readers and the number of tag categories are $m = 50$ and $u = 1{,}000$, respectively. The number of tags n varies from 50,000 to 100,000 with $\frac{n}{u}$ per category. The readers are deployed in grid on the ceiling of the simulated system. The number of reference readers for tag positioning by (1) is set to $h = 3$.

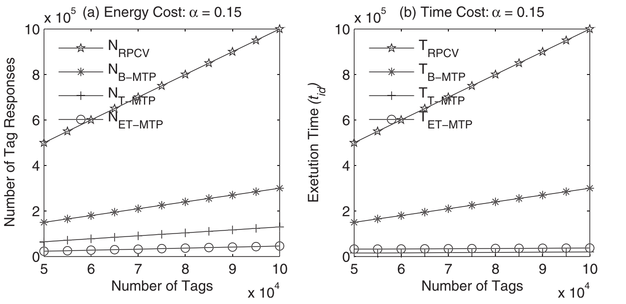

Fig. 7. Analytical performance comparison of RPCV, B-MTP, T-MTP, and ET-MTP.

Each reader has 38 tunable transmission power levels as the representative RFID positioning scheme in [22]. 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 $\frac{s}{96}t_{id}$. The transmission time of the category ID is therefore $t_{cid} = \frac{\lceil \log_2 u \rceil}{96}t_{id} = \frac{10}{96}t_{id}$. Following the system configuration of RPCV, all inventory items are with the same volume. In this case, each reader covers on average $1{,}000 \leq \frac{n}{m} \leq 2{,}000$ tags and 12 bits is enough to express the probability $p_k = \frac{m}{n}$ by (3). Thus, the transmission time of p_k can be estimated by $\frac{12}{96}t_{id}$.

6.2 Comparison Other: RPCV [1]

In RPCV simulation [1], 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 on the number of tag responses and the execution time of RPCV, denoted as N_{RPCV} and T_{RPCV}, respectively, as the following:

$$N_{RPCV} = 10n, T_{RPCV} = 10nt_{id}. \quad (4)$$

We hereby compare analyzed optimal performances of RPCV and our protocols in Fig. 7 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 (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.

6.3 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, we randomly pick αn tags and then randomly place them 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 4.3) to avoid false negatives, because we are interested primarily in time efficiency and energy efficiency in this paper.

Fig. 8 reports the results under various scenarios in comparison with RPCV. As we 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 B-MTP. When $\alpha = 0.05$ as shown in Figs. 8a and 8b, compared with RPCV, T-MTP can averagely increase the time efficiency by up to 93 percent, and ET-MTP can averagely increase the energy efficiency by up to 95 percent. When $\alpha = 0.15$, the time efficiency improvement and the energy efficiency improvement can still be as much as 90 percent (Fig. 8f) and 91 percent (Fig. 8e), respectively.

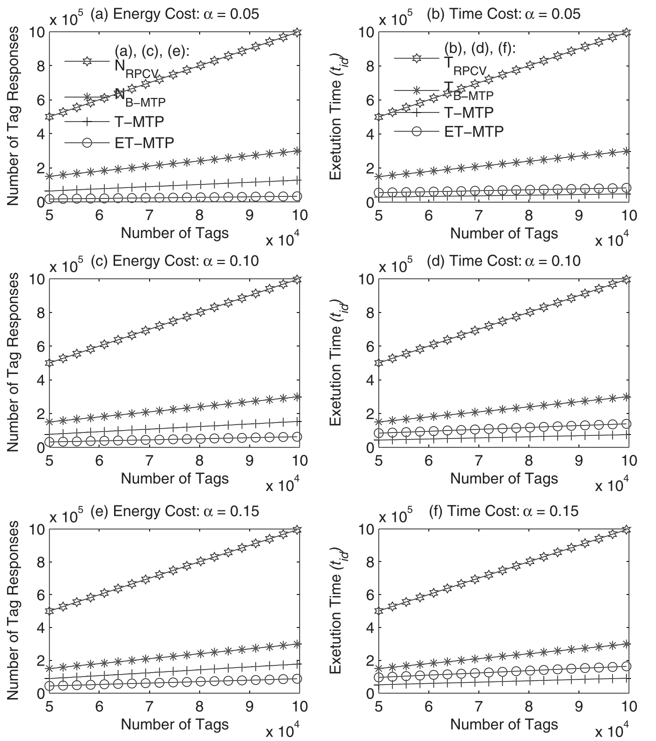

Fig. 8. Performance comparison of RPCV, B-MTP, T-MTP, and ET-MTP with varying tag number n and misplacement ratio α.

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

6.4 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 be affected too much. Without considering the reader collision problem [26], time lower bounds for m readers collecting n tag IDs with sequential and parallel reading are nt_{id} and $\frac{nt_{id}}{m}$, respectively. Fig. 9 plots the lower bound with varying m and n. Parallel reading provides a promising chance of time efficiency improvement as shown in Fig. 9.

7 D-MTP: Distributed Misplaced-Tag Pinpointing Protocol

This section proposes *D-MTP*, a distributed protocol that enables each reader to independently detect misplaced tags.

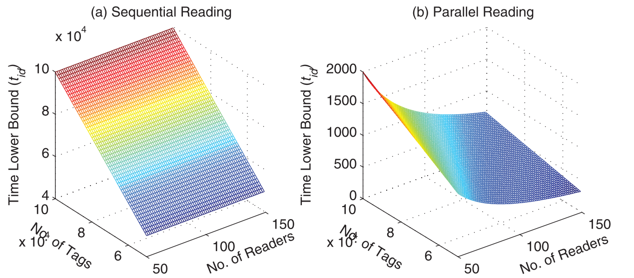

Fig. 9. Analytical performance comparison of sequential and parallel reading.

Our analysis shows that D-MTP is more time efficient than T-MTP and even more energy efficient than ET-MTP in some cases.

7.1 Motivation and Main Idea

Although T-MTP and ET-MTP activate each reader to query all categories of tags, we observe that not all readers cover all the categories. This observation is especially evident in large RFID systems where a single reader can cover only a small fraction of tags. As for the MTP problem, we even must deliberately make sure that each reader cover only some, but not all, categories of tags. If each reader would cover all categories, we would have not been able to leverage reader positions to quickly detect misplaced tags as we do in T-MTP and ET-MTP.

Motivated by the above observation, we can detect misplaced tags in a more efficient way. The intuition is that if each reader learns which categories it covers, it can simply broadcast those category IDs and inform tags not in those categories to respond—misplaced tags exist if it receives any response. A desirable side product of the intuition is distributed misplaced-tag detection—a reader can independently verify whether any misplaced tags are within its coverage.

We expect D-MTP to be more efficient than T-MTP and ET-MTP in time efficiency and even in energy efficiency. D-MTP is more time efficient because it requires each reader to query only categories it covers but T-MTP and ET-MTP require each reader to query all categories. D-MTP could be more energy efficient because it requires only misplaced tags to respond but T-MTP or ET-MTP in addition require all or a fraction of properly placed tags to respond, respectively.

Next, we will first investigate how D-MTP learns which categories covered by each reader, and then analyze its performance.

7.2 Learning Category Coverage from Tag Monitoring

An RFID system may periodically run various operations to implement important functions, such as missing-tag detection and identification [13], [14], [15], information collection [19], and continuous scanning that monitors a dynamic RFID system with tags frequently moved in or out [28], [34]. These operations monitor tags in real time. We can leverage the information from tag monitoring to deduce which categories covered by each reader. For example, the outputs of continuous scanning are the IDs of all present tags. Examining the IDs of tags covered by a reader, we can easily extract their category IDs.

Misplaced-tag detection using tag monitoring statistics may, however, induce both false negatives and false positives. False negatives arise from tag monitoring statistics that contain data of misplaced tags. Since it is hard to guarantee that tag monitoring operations only run when all tags are correctly placed, data of misplaced tags may contaminate tag monitoring statistics. Using such contaminated tag monitoring statistics, a reader cannot detect misplaced tags that are already in the statistics, inducing false negatives. We can mitigate the problem of false negative by filtering out misplaced tags related data in the statistics. Learning from past detections is therefore the other way for D-MTP to infer which categories covered by each reader. See the next section.

False positives arise from obsolete tag monitoring statistics that fail to capture system update after the statistics is obtained. Possible system update operations include rearrangement and replenishment. Rearrangement follows new placement plan and places some categories of tags somewhere else in the system. Replenishment moves more tags into the system and places them next to where stay their same categorized peers. In both cases, some tags may intrude communication regions of readers that do not cover their categories according to the statistics, and therefore trigger false positives. Although it is not practical to prohibit any system update after we obtain latest tag monitoring statistics, it is practical for us to be aware of any system update operation launched ever since. If system update happens between we obtain the statistics and we run MTP protocols, we have to apply our previously proposed protocols (e.g., B-MTP, T-MTP, or ET-MTP) to detect misplaced tags, capturing real-time system status and thus avoiding false positives.

7.3 Learning Category Coverage from Past Detections

D-MTP can learn which categories a reader covers from detection results of our previously proposed protocols (e.g., B-MTP, T-MTP, or ET-MTP). In B-MTP (Section 3), when a reader has collected all the IDs of tags it covers, it can easily extract their category IDs. In T-MTP and ET-MTP (Sections 4 and 5), when a reader has queried all categories, it covers the categories that respond to the queries. Let C_i represent the set of categories covered by a reader r_i, and M_i the set of categories of detected misplaced tags within r_i's coverage. Then, we can derive $\hat{C}_i$, the set of categories that r_i correctly covers, by

$$\hat{C}_i = C_i - C_i \cap M_i. \tag{5}$$

After getting the set $\hat{C}_i$ for every reader $r_i \in R$, the reader r_i can detect misplaced tags in any categories other than those in $\hat{C}_i$.

We now discuss misplaced-tag detection accuracy of MTP using $\hat{C}_i$ learned from detection results of B-MTP, T-MTP, or ET-MTP. As we discussed in Section 7.2, false positives will arise from the statistics that fail to capture latest system update. To avoid them, we still need to verify that no such system update occurs after we collect $\hat{C}_i$. Whether we could avoid false negatives due to contaminated statistics in Section 7.2 depends on which of B-MTP, T-MTP, and ET-MTP we use to generate $\hat{C}_i$. B-MTP can successfully avoid them because B-MTP uses tag-wise positioning and induces no false negatives. T-MTP and ET-MTP can eliminate misplaced categories that they can detect, by (5). Since T-MTP and ET-MTP may induce false negatives, we cannot rule out misplaced categories that they fail to detect. But compared with tag monitoring statistics, B-MTP, T-MTP, and ET-MTP still try the best to generate less contaminated statistics that induce fewer false negatives.

7.4 Performance Analysis

We analyze time efficiency and energy efficiency of D-MTP compared with that of T-MTP and ET-MTP. Since among the proposed protocols [21], T-MTP and ET-MTP are the most time efficient and the most energy efficient, respectively, we compare D-MTP's time efficiency with T-MTP's and D-MTP's energy efficiency with ET-MTP's. Our analysis is convincing to show that D-MTP is more time efficient than T-MTP and has chances of being more energy efficient than ET-MTP.

We first analyze D-MTP's time efficiency with respect to the execution time. Recall that we use D-MTP when we ensure that no system update could induce false positives. Under the same scenario with a certain amount of misplaced tags, D-MTP and T-MTP take similar time to locate them. We only need to analyze the time for D-MTP to detect misplaced tags if any in each category—the same result as that of T-MTD (Section 4.2.1). We denote the time for D-MTP and T-MTP to detect misplaced categories as T'_{D-MTP} and T'_{T-MTP}, respectively. We have derived in Section 4.4 that

$$T'_{T-MTP} = \sum_{k=1}^{u}\sum_{i=1}^{m}(t_{cid} + t_{10b}) = um(t_{cid} + t_{10b}).$$

Next, we will derive T'_{D-MTP} and prove it less than T'_{T-MTP}.

The time T'_{D-MTP} consists of two parts, the time for detecting whether misplaced categories exist and the time for verifying which categories they are if any. To detect whether misplace categories exist within a reader r_i's coverage, the reader r_i queries by broadcasting all category IDs in $\hat{C}_i$ (5). Upon receiving the query message, tags not in the broadcasted categories respond with a 10-bit random string. The reader r_i then determines that it covers no misplaced tag if it receives an empty slot, one misplaced tag if a singleton slot, or multiple misplaced tags if a collision slot. Then, in the first step, the time for r_i to detect the existence of misplaced tags is therefore $|\hat{C}_i|t_{cid} + t_{10b}$. To facilitate the analysis of the time for distinguishing the categories of misplaced tags, we introduce p_i and define it as follows:

$$p_i = \begin{cases} 0, & \text{if } r_i \text{ receives an empty slot,} \\ 1, & \text{if } r_i \text{ receives a nonempty slot.} \end{cases}$$

In the second step, only the readers with $p_i = 1$ continue to determine the exact categories that misplaced tags belong to. A simple method is that r_i queries through broadcasting one category ID in $C - \hat{C}_i$ after another. Responses corresponding to any category ID reveals that some tags in this category are misplaced. For ease of determining the number of misplaced tags, we still use 10-bit responses. Using this method, it takes $|C - \hat{C}_i|(t_{cid} + t_{10b})$ for r_i to determine all the misplaced categories covered by r_i.

Combining the time in the above two steps, we therefore have

$$\begin{aligned} T'_{D-MTP} &= \sum_{i=1}^{m}(|\hat{C}_i|t_{cid} + t_{10b} + p_i|C - \hat{C}_i|(t_{cid} + t_{10b})) \\ &\le \sum_{i=1}^{m}(|\hat{C}_i|t_{cid} + t_{10b} + |C - \hat{C}_i|(t_{cid} + t_{10b})) \\ &= \sum_{i=1}^{m}(|C|(t_{cid} + t_{10b}) - (|\hat{C}_i| - 1)t_{10b}) \\ &< \sum_{i=1}^{m}(|C|(t_{cid} + t_{10b})) = T'_{T-MTP}. \end{aligned}$$

We then analyze D-MTP's energy efficiency with respect to the number of tag responses. Under the same scenario with a certain misplaced tags, D-MTP, T-MTP, and ET-MTP require similar number of tag responses to locate them. Therefore, similar to the analysis of D-MTP's time efficiency, we only consider N'_{D-MTP}, the number of tag responses for D-MTP to detect misplaced categories. Given the misplacement ratio α, it is straightforward that

$$N'_{D-MTP} = 2\alpha n,$$

because each misplaced tag needs to respond twice—one to the query of existence of misplaced tags and the other to the query of which are misplaced categories. Let N'_{T-MTP} and N'_{ET-MTP} denote the number of tag responses for T-TMP and ET-MTP to detect misplaced categories, respectively. Retrospecting to the performance analysis of T-MTP (Section 4.4) and ET-MTP (Section 5.4), we have

$$\begin{aligned} N'_{T-MTP} &> n, \\ N'_{ET-MTP} &= \sum_{k=1}^{u} p_k n_k > \frac{n}{m}\sum_{k=1}^{u} p_k. \end{aligned}$$

Therefore, by solving $N'_{D-MTP} < N'_{T-MTP}$ and $N'_{D-MTP} < N'_{ET-MTP}$, we conclude that

- if $\alpha < 0.5$, D-MTP is more energy-efficient than T-MTP;
- if $\alpha < \frac{1}{2m}\sum_{k-1}^{u} p_k$, D-MTP is even more energy efficient than ET-MTP.

8 Discussion

8.1 Tag Mobility

This section discusses the MTP problem in the presence of tag mobility. If mobile tags exist, we cannot simply apply the preceding protocols but need to distinguish misplaced tags from mobile tags, which could be carried by roaming machines or wandering customers. The intuition is to first track detected misplaced tags for a while and then analyze their location traces. If a detected misplaced tag hovers around the same location within a certain time interval, it is likely to be misplaced. If a detected misplaced tag moves from place to place within the time interval, it is likely to be mobile.

One natural approach to obtaining detected misplaced tags' traces is using multiround detection. Using one of the preceding protocols (e.g., B-MTP, T-MTP, ET-MTP, or D-MTP), we run it several times to obtain location traces of detected misplaced tags. Assume that we need x locations to verify whether a detected misplaced tag is really misplaced or mobile. Let $l_i(t_j)$ ($i \in [0, x-1]$) denote the $(i+1)$th location in a tag t_j's location trace. Then, we can distinguish misplaced tags from mobile tags using the following condition:

$$\frac{\sum_{i=0}^{x-1} |l_i(t_j) - l_0(t_j)|}{x} < \delta, \tag{6}$$

where $|l_i(t_j) - l_0(t_j)|$ is the distance between locations $l_i(t_j)$ and $l_0(t_j)$, and δ is a threshold that can be set according to localization accuracy. If the condition in (6) is satisfied, t_j is likely to be stationary and therefore really misplaced. Otherwise, t_j is mobile and could be carried by machines or people roaming through the system.

Certainly tag mobility places a heavy overhead burden on MTP solutions, especially when many mobile tags move frequently. We therefore do not encourage pinpointing misplaced tags with mobile tags available unless the necessity outweighs the cost. More thorough investigation of tag mobility is left for our future work.

8.2 Channel Reliability

This section discusses the impacts of channel errors, packet loss on the proposed protocols, and suggests countermeasures against the potential impacts.

Both channel errors and packet loss may induce false negatives to the proposed protocols. For B-MTP, false positives due to channel errors occur when 1) queries from readers to tags are interfered and tags cannot determine whether to respond; and 2) tags normally respond but responses from tags to readers are interfered. In both cases, some tags cannot successfully communicate with readers and thus avoid being detected if they are misplaced. For T-MTP, ET-MTP, and D-MTP, false negatives due to channel errors occur only when queries from readers to tags are interfered and tags cannot determine whether to respond. False negatives induced by packet loss are easier to infer—if queries from readers to misplaced tags or responses from misplaced tags to readers lost, we could hardly detect those misplaced tags and thus encounter false negatives.

To guarantee channel reliability for RFID communication, it is common to use a transmission power level high enough to drown the background noise. Certainly higher transmission power causes more energy consumption. Yet, packet loss is more challenging and may not be addressed by solely using a high transmission power level. We may have to resort to multiround detection for guaranteeing detection accuracy at the cost of reduced time efficiency. When adopting the above countermeasures, the proposed energy- and time-efficient protocols (e.g., T-MTP, ET-MTP, and D-MTP) become more favorable than B-MTP and the state-of-the-art RPCV [1].

9 Conclusion and Future Work

We have studied efficient MTP solutions against misplacement errors, a major concern in production economics due to their serious impact on profit. Departing from previous research that collects a large amount of data, this paper investigates efficient MTP solutions from the perspective of communication protocol design.

We propose a series of protocols toward efficient MTP solution in large RFID systems, even in a distributed manner and robust against tag mobility. T-MTP detects misplaced tags based on reader vectors instead of tag vectors. It yields significantly increased time efficiency and energy efficiency, compared with basic solutions based on tag-wise positioning. ET-MTP caters for the trend of applying more and more popular active tags with self-equipped batteries. In favor of energy saving, ET-MTP requires only a fraction of tags to respond. To address the MTP problem in a distributed manner, D-MTP enables each reader to independently detect misplaced tags. D-MTP is more time efficient than T-MTP and even could be more energy efficient than ET-MTP. Analysis and experiments validate 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. Finally, we further discuss how to apply the proposed protocols in scenarios with mobile tags.

Our future work lies in the following three directions. First, we now only consider sequential reading. As we discussed in Section 6.4, parallel reading can yield higher time efficiency than can sequential reading. A promising topic is thus to adjust existing multireader scheduling protocols (e.g., in [26]) to the MTP problem or even to design a new scheduling method that fits in better. Second, the positioning accuracy of the scheme in [22] may not satisfy requirements of certain applications. Inspired by the proliferation of sensor network localization [35], we could borrow some ideas therein to improve tag positioning accuracy. Third, although evaluating research on large-scale RFID systems depends primarily on simulation nowadays, we urge our future work to evaluate and refine the proposed protocols in real RFID systems.

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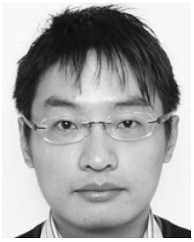

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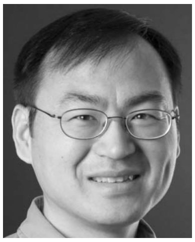

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