Efficient Unknown Tag Identification Protocols in Large-Scale RFID Systems

Xiulong Liu, Keqiu Li*, Geyong Min, Kai Lin, Bin Xiao, Yanming Shen, Wenyu Qu

Abstract—Owing to its attractive features such as fast identification and relatively long interrogating range over the classical barcode systems, Radio-Frequency Identification (RFID) technology possesses a promising prospect in many practical applications such as inventory control and supply chain management. However, unknown tags appear in RFID systems when the tagged objects are misplaced or unregistered tagged objects are moved in, which often causes huge economic losses. This paper addresses an important and challenging problem of unknown tag identification in large-scale RFID systems. The existing protocols leverage the Aloha-like schemes to distinguish the unknown tags from known tags at the slot level, which are of low time-efficiency, and thus can hardly satisfy the delay-sensitive applications. To fill in this gap, two filtering-based protocols (at the bit level) are proposed in this paper to address the problem of unknown tag identification efficiently. Theoretical analysis of the protocol parameters is performed to minimize the execution time of the proposed protocols. Extensive simulation experiments are conducted to evaluate the performance of the protocols. The results demonstrate that the proposed protocols significantly outperform the currently most promising protocols.

Index Terms—RFID Technology; Unknown Tag Identification; Time Efficiency; Optimization.

1 Introduction

1.1 Background Knowledge

Owing to its attractive features including remote access, multiple simultaneous access, non-line-of-sight reading, computational ability, and relatively large rewritable memory over the conventional barcode systems, Radio-Frequency Identification (RFID) technology has been widely used in many practical applications such as localization [1], [2], [3], [4], supply chain management [5], [6], [7], [8], [9], and inventory control [10], [11], [12], [13], [14]. In these applications, an RFID system consists of a back-end server, a single (or multiple) reader(s) and a large number of tags. The RFID reader is a device equipped with a dedicated power source and has adequate computing power and storage capacity. The back-end server sends commands to the readers via a high-rate network link in order to control the readers to read/write data from/to the tags. An RFID tag is a microchip combined with an antenna that has only limited computing power and storage capacity. RFID tags are usually labeled in the designated objects, and each tag has a 96-bit unique ID to indicate the information (e.g., product price, production date, and place of origin, etc.) of the tagged objects. The RFID tags are generally classified into two categories. The passive tag has no battery supply and transmits data by reflecting the received signals from the reader. The passive tag is only activated when it is within the vicinity of a reader; and he active tag is powered by an internal battery and has longer communication ranges over the passive one. RFID systems mostly work in a Reader Talk First (RTF) mode where a reader queries the tags within its vicinity and the tags respond over a common wireless medium [15].

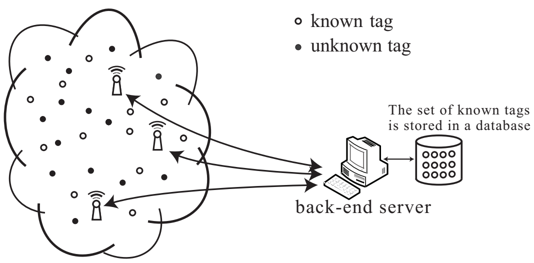


Fig. 1: The problem statement of unknown tag identification.

1.2 Motivation and Problem Statement

According to the statistics presented in [16], Raman, DeHoratius and Ton reported that the consumers cannot find 16 percent of inventory items on average in the stores because of the misplacement of those items. The chilled food that is misplaced at the zone without refrigeration equipment and not discovered in time

- *X. Liu, K. Li, K. Lin and Y. Shen are with the School of Computer Science and Technology, Dalian University of Technology, No 2, Linggong Road, Dalian 116023, China. E-mail: keqiu@dlut.edu.cn.*
- *G. Min is with the College of Engineering, Mathematics and Physical Sciences, University of Exeter, Exeter, EX4 4QF, United Kingdom. E-mail: G.Min@exeter.ac.uk*
- *B. Xiao is with the Department of Computing, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China. E-mail: csbxiao@comp.polyu.edu.hk.*
- *W. Qu is with the School of Information and Technology, Dalian Maritime University, Dalian 116026, China. E-mail: eunice.qu@gmail.com.*

will decay quickly. More seriously, in the warehouse management, a lighter that is misplaced in the area of alcohol may cause fatal safety problem [17]. Hence, in the warehouse management, a practically important task is to identify the misplaced items efficiently. Obviously, manual checking is seriously laborious and is of low accuracy. Fortunately, RFID technology can be used to solve this problem.

As illustrated in Fig. 1, each item in the scanning area is attached with an RFID tag. The tag IDs of the normal items are stored in the database of the back-end server. However, the tag IDs of the misplaced items are not available in the database and the corresponding tags are referred to as *unknown tags*. The problem studied in this paper is to identify the unknown tags exactly.

1.3 Prior Art and Limitation

A straightforward solution to unknown tag identification is to borrow directly the pure tag identification schemes [18], [19], [20], [21], [22], [23], [24] to identify all tags in the scanning area. Then, it is possible to obtain the IDs of the unknown tags by comparing the identified IDs with those stored in the database. However, this scheme is seriously time-consuming because it needs to re-collect a large number of known tag IDs, which renders inappropriateness for applications with stringent delay requirement. To the best of our knowledge, the existing protocols specifically for addressing the problem of unknown tag identification include: (1) the algorithm of Collect Unknown tags (referred to as the CU protocol) proposed in [12]; and (2) a set of protocols, namely BUIP, BUIP-CE and BUIP-CF, proposed in [25]. In what follows, we will briefly present the principle of these protocols.

The CU protocol is a variant of the well-known Framed Slotted Aloha mechanism [18]. Each tag randomly picks a slot in a time frame based on the hashed value of its ID with a random seed received from the reader. Because the reader has full knowledge of the known tag IDs, the random seed and the hash function, it is able to predict which slots are expected empty slots (i.e., not occupied by any known tags). The reader sends signals to make the tags reply and then checks the slots one by one. The tags that are active in the expected empty slots are identified as unknown tags. The classical Enhanced Dynamic Framed Slotted ALOHA (EDFSA) protocol [18] is further adopted to identify the IDs of the active unknown tags. The above process is repeated for multiple rounds so as to achieve a given identification accuracy.

The CU protocol only leverages the expected empty slots to detect the unknown tags, whereas, the other slots are not utilized fully. Moreover, all the known tags participate in every round, which seriously interfere the unknown tag detection, especially when there is a large number of known tags. To overcome these drawbacks of the CU protocol, the protocols proposed in [25] adopt not only the expected empty slots to label the unknown tags but also the expected singleton slots to deactivate the known tags for the sake of preventing them from interfering the detection of unknown tags. Specifically, if one and only one tag responds in an expected singleton slot, this must be a known tag. Then, the reader sends an ACK signal to deactivate this known tag (i.e., telling it to enter the sleep state). On the other hand, if one or more tags respond in an expected empty slot, all of them must be unknown tags. The reader then sends an NACK signal to label them (i.e., telling them not to participate in the next round, but still keep active). Some known/unknown tags may be deactivated or labeled in each round, and they will not participate in the following rounds. The above process is repeated for multiple rounds until all known tags are deactivated. As a result, the remaining active tags are all unknown ones.

Both CU [12] and the protocols [25] are based on the Aloha-like schemes at the slot level, which is of low time-efficiency and renders them far from efficiency.

1.4 Proposed Approaches and Main Contributions

The obstacle to efficient identification of unknown tags is caused by the fact that the known tags interfere and make the responses from the unknown tags buried in overwhelming “noises” [12]. The challenge is how to efficiently “separate” the unknown tags from the known ones, and then we are able to identify the unknown tags without the interference from the known tags.

To this end, this paper first investigates a Filtering-based Unknown Tag Identification (FUTI) protocol at the *bit level*. Specifically, the reader constructs a cost-effective filter by mapping all the known tag IDs to it. In the filter, ‘1s’ indicate at least one known tags are mapped to these bits; ‘0s’ indicate none of the known tags is mapped to these bits. The constructed filter is broadcasted by the reader. If a tag finds its representative bit is ‘0’, it labels itself. Clearly, the labeled tags are unknown tags. Multiple rounds are repeated until the expected percentage of the unknown tags are labeled. The EDFSA protocol [18] is then used to collect the labeled unknown tags.

Based on the proposed FUTI protocol, we further develop an Interactive Filtering-based Unknown Tag Identification (IFUTI) protocol. Different from the FUTI protocol, IFUTI leverages two interactive filters to filter out not only the unknown tags but also facilitate the identification of the labeled unknown tags. The simulation results demonstrate that the proposed FUTI and IFUTI protocols have their own advantages in different application scenarios. Specifically, in an

RFID system with high density of unknown tags, the IFUTI protocol outshines FUTI because two interactive filters are used in IFUTI to accelerate the identification of unknown tags. In contrary, in an RFID system with low density of unknown tags, IFUTI does not ourperform FUTI any more due to the double transmission overhead of the interactive filters.

Theoretical analysis of the protocol parameters is also presented to minimize the execution time of the proposed schemes. Extensive simulations are conducted to evaluate the performance of the proposed protocols, and the results show that they significantly outperform the existing advanced protocols.

The major contributions of this paper can be summarized as follows:

1) This paper studies an important and challenging problem of unknown tag identification. We first design a cost-effective filter to detect the unknown tags, and then propose the Filtering-based Unknown Tag Identification (FUTI) protocol.
2) We further design a reverse filter to improve FUTI, thereby facilitating the identification of unknown tags, and thus propose the Interactive Filtering-based Unknown Tag Identification (IFUTI) protocol that is more useful in RFID systems with high density of unknown tags.
3) This paper also performs the theoretical analysis of configuration of the filter length in order to minimize the execution time of the proposed protocols and configuration of the minimum round count so as to meet the predefined identification accuracy.
4) Extensive simulation experiments are conducted to evaluate the performance of the proposed protocols. The results demonstrate that the new protocols considerably outperform the existing advanced protocols.

The rest of this paper is organized as follows. The related work is reviewed in Section 2. Section 3 presents the system model. We propose the FUTI and IFUTI protocols and present the theoretical analyses in Sections 4 and 5, respectively. In Section 6, extensive simulation experiments are conducted to evaluate the performance of the proposed protocols. Finally, this paper is concluded in Section 7.

2 RELATED WORK

In RFID applications, one of the most fundamental tasks is tag identification, which has attracted extensive research efforts from academy and industry. The pure tag identification protocols aim at identifying all tag IDs in a *static* RFID system. The corresponding solutions are generally classified into two categories: Aloha-based protocols [18], [19], [20] and Tree-based protocols [21], [22], [23], [24].

The basic principle of the Aloha-based protocols is presented as follows. The reader first broadcasts the frame size f and a random number R to the tags in the interrogating range. Each tag uses the received parameters f and R to pick a slot s in the frame to relay the ID information, where $s = h(ID, R) \mod f$. In any slot, if one and only one tag responds, the reader is able to successfully obtain the ID information of the tag. This type of slots is referred to as singleton slots. An RFID tag that is successfully identified in a singleton slot will keep silent for the rest of the identification processes. If multiple tags simultaneously transmit their IDs in a common slot, the responses are garbled due to signal collision and thus retransmission is required. Multiple frames are repeated until all the tags are identified [15].

A Tree-based protocol [21], [22], [23], [24] organizes all IDs in a binary tree where the height of this tree is equal to the length of a tag ID. Each left branch of the tree is marked by '0' and each right branch by '1'. The reader first queries the tags by broadcasting a prefix '0'. All the tags whose IDs start with '0' answer this query. If the reader has a successful read (i.e., exactly one tag answers) or an empty read (i.e., no tag answers), the reader queries the tags by broadcasting a prefix '1', and all the tags whose IDs start with '1' answer this query. If the reader senses a signal collision, it will generate two new query prefixes by appending a '0' and a '1' to the previous query prefix. And the reader repeats the above process by querying the tags with the two new query prefixes, which continues until all the tags have been identified [24].

In reality, the RFID system is dynamic, e.g., some tagged items may be missing due to theft; and some unknown (new) tagged items may appear because of misplacement. It is of great importance to propose efficient solutions for monitoring the dynamic RFID system.

In terms of missing tag problems, Tan *et al.* [11] studied the Trust Reader Protocol (TRP) to detect the missing-tag event with a predefined confidence level when the number of the missing tags exceeds the tolerance threshold. In TRP, all tags participate in the detection process. The performance of TRP decreases when the cardinality of tags increases. To improve the time-efficiency and energy-efficiency of TRP, Luo *et al.* [14] introduced the sampling idea, and thus proposed the Efficient Missing-tag Detection (EMD) protocol, where the detection result on the sampled tags is used to probabilistically reflect the whole intactness of RFID systems. The authors indicated that TRP is a special case of EMD. Moreover, a time-energy tradeoff is also presented in [14]. Based on their prior work, Luo *et al.* [26] investigated a multi-hash approach to increase the utilization of time frame, and thus the performance of the missing tag detection protocol is improved. The above schemes can detect the missing tag event only but are unable to find out which specific tags are missing and thus fails to provide the details of the missing tags. To identify the exact missing tags, Li *et al.* [27] proposed the Iterative ID-free Protocol (IIP), which is a variant of the Framed Slotted Aloha mechanism. In IIP, the reader identifies the missing tags by observing the status of the slots. Specifically, the reader asserts a tag is missing if the corresponding slot is supposed to be singleton but turns out to be empty. In [28], Zhang *et al.* investigated the problem of missing tag identification in the multi-reader scenarios, where all the readers perform *synchronized and parallel* scans. In [29], Zheng *et al.* proposed a Physical-layer Missing Tag Identification scheme which utilizes the compressive sensing technique to improve the time-efficiency.

This paper studies the problem of unknown tag identification. As aforementioned, the above pure tag identification protocols can be directly borrowed to address this problem. By comparing all the identified IDs with the known tag IDs, it is possible to identify the unknown tags. However, since the IDs of the known tags have already been stored in the back-end server, recollecting a large number of known tag IDs is obviously inefficient. The protocols reported in [12], [25] suppress the known tags from responding, while keeping the unknown ones active to be identified. Their basic principles have been briefed in Section 1.3. Since these two protocols use the classical Framed Slotted Aloha mechanism to detect the unknown tags at the *slot level*, they are of low time-efficiency and remain large room to be improved.

3 System Model

3.1 Assumption and Problem

We consider an RFID system that consists of a single reader, N known tags and M unknown tags, where the IDs of N known tags are stored in the database of the back-end server but the IDs of unknown tags and even the number of unknown tags, M, are not available in the database. All tags are within the interrogating range of this reader. The known tag set is denoted as T_{known}, i.e., $T_{known} = \{t_1, t_2, \ldots, t_i, \ldots, t_N\}$; and the unknown tag set is denoted as $T_{unknown}$, i.e., $T_{unknown} = \{tu_1, tu_2, \ldots, tu_i, \ldots, tu_M\}$. Each tag has a unique ID and is equipped with the same uniform hash generator $H(\cdot)$. In this paper, we first consider the single reader case and then extend our solutions to the multi-reader case.

The problem addressed in this paper is to efficiently identify the *unknown* tags with a given accuracy α, i.e., a fraction α of the unknown tags are expected to be identified. For example, if α is predefined to 99%, when 100 unknown tags appear in the RFID system, 99 unknown tags among them should be identified on average. The performance metric considered in this paper is time-efficiency.

3.2 Communication Overview

The reader communicates with the tags through a one-hop low-rate wireless network link. In contrast, the reader and the back-end server communicate through a high data-rate wireless or wired link. Because the communication delay between the reader and back-end server is so minor that it can be ignored, we only consider the communication time between the reader and tags in this paper. The reader continuously sends synchronization signals to create a slotted time frame. The interactive communications are in the Reader Talks First (RTF) mode [30], i.e., the reader queries the tags first and a tag responds according to the reader's commands. In [27], Li *et al.* presented a method of classifying the time slots based on their length: *tag slots*, *long-response slots* and *short-response slots*. The slot that can support transmission of 96-bit ID is called a tag slot, whose length is denoted as t_{tag}. The slot that can support transmission of 10-bit information is referred to as a long-response slot, whose length is denoted as t_{long}. And the slot that can only support transmission of 1-bit information is called a short-response slot, whose length is denoted as t_{short}. According to the specification of the Philips I-Code system [31], the rate from a tag to a reader is $53Kb/s$ and the rate from a reader to a tag is $26.5Kb/s$. Any two consecutive transmissions (from a tag to a reader or vice versa) are separated by a waiting time of $302us$. For simplicity, this paper assumes that the data rate of the reader-to-tag link is the same as that of the tag-to-reader link. Following the parameter settings in [13], [14], [27], [28], [32], t_{tag}, t_{long} and t_{short} are set to $2.4ms$, $0.8ms$ and $0.4ms$, respectively. Table 1 summaries the notations that are used throughout this paper.

TABLE 1: Notations.

Symbols	Descriptions
N	The number of known tags
M	The number of unknown tags
T_{known}	The set of known tags
$T_{unknown}$	The set of unknown tags
t_{tag}	The tag slot
t_{long}	The long-response slot
t_{short}	The short-response slot
F	Filter vector
f	The length of the filter
R	The random seed that is fresh in each round
$\bigotimes$	The XOR operation
$H(\cdot)$	The hash function with a uniform random distribution
e	The natural constant
α	The identification accuracy
L_1/L_2	The minimum round count that needs to be executed by FUTI/IFUTI to satisfy the given identification accuracy α

4 A Filtering-based Unknown Tag Identification Protocol

To address the problem of unknown tag identification in a time-efficient way, this section proposes a

Filtering-based Unknown Tag Identification (FUTI) protocol. After presenting the FUTI protocol design, we further analyze the parameter settings to achieve its best time-efficiency as well as the required identification accuracy.

4.1 Protocol Design

The proposed FUTI protocol consists of two phases: (i) *Unknown Tags Filtering* phase, in which a fraction α of unknown tags are expected to be labeled; (ii) *Unknown Tags Identification* phase, in which only the labeled unknown tags are identified without the interference from the known tags. In the following, we present the operations of these two phases in detail.

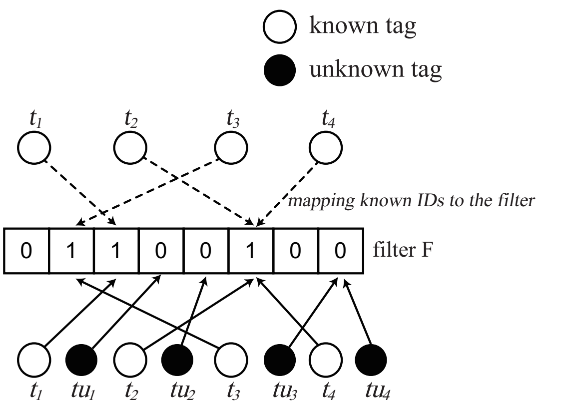


Fig. 2: Exemplifying the basic principle of the Filtering-based Unknown Tag Identification protocol.

4.1.1 Phase I: Unknown Tags Filtering

As illustrated in Fig. 2, the reader maps the IDs of all known tags to a filter F with f bits. Specifically, an arbitrary known tag t_i with ID_i is mapped to the γ_i^{th} bit in the filter F based on a uniform hash function $H(\cdot)$, where $\gamma_i = H(ID_i, R) \mod f$ (R is a random seed number that is fresh in each round). We refer to the γ_i^{th} bit as the *representative* bit of tag t_i. If one or more known RFID tags are mapped to the γ_i^{th} bit in the filter F, this bit is set to '1'. On the contrary, if none of the known RFID tags is mapped to the γ_i^{th} bit, this bit is set to '0'.

Then, the reader broadcasts the used parameters R, f as well as the filter F to all tags including both known tags and unknown tags. Obviously, the locations of '1s' in the filter F indicate the mapping distribution of known tags. Each tag employs the *same* hash function $H(\cdot)$, the received parameters R and f to calculate its representative bit, specifically, using $H(ID_i, R) \mod f$ as the index of its representative bit. It is easy to draw the following conclusions: (i) the representative bits of the known RFID tags in the filter F are always '1s'; (ii) the representative bits of some unknown RFID tags are '1s' when they select the bits to which one or more known RFID tags are mapped; (iii) the representative bits of some unknown RFID tags are '0s' when they select the bits to which none of the known RFID tags are mapped. During the process of receiving the filter F, each tag checks its representative bit in F. For an arbitrary tag, if its representative bit is found to turn out to be '0', it asserts that it is an unknown tag and labels itself. In each round, some unknown RFID tags may be labeled. And the more rounds are repeated, the more unknown tags are expected to be labeled. This filtering process is repeated until a fraction α of the unknown tags are labeled.

4.1.2 Phase II: Unknown Tags Identification

Only the labeled unknown tags participate in this tag identification phase. The same as CU [12] and the protocols in [25], we employ the EDFSA protocol [18] to identify the labeled unknown tags.

As the *Unknown Tags Filtering* phase is the highlight and unique feature of the proposed FUTI protocol, we mainly focus on optimizing the parameters involved in the first phase, specifically, the filter length f and the minimum round count L_1. This FUTI protocol was reported in the conference version of this paper [33].

4.2 Determining the Optimal Filter Length f

In an arbitrary round k of the *Unknown Tags Filtering* phase, a certain unknown tag can be labeled when it selects a bit in the filter F to which no any known tag is mapped. The probability that a certain unknown tag can be labeled in this round, denoted as P_k, is given as follows

$$P_k = \binom{f}{1} \times \frac{1}{f} \times (1 - \frac{1}{f})^N \approx e^{-\frac{N}{f}}, \tag{1}$$

where N is the number of known tags and f is the filter length. Given the fact that f is normally very large, P_k can be simplified to $e^{-\frac{N}{f}}$ in Eq. (1), where e is the natural constant. Let M denote the number of unknown tags. Each of the M unknown tags is expected to be labeled with the probability P_k in this round. Hence, the number of unknown tags that are labeled in this round, denoted as $\aleph_1$, is expected to be $M \times P_k$, i.e., $\aleph_1 = M \times e^{-\frac{N}{f}}$.

In what follows, we will analyze the time cost of this round. To begin with, one *tag slot* (i.e., t_{tag}) is adequate for the reader to broadcast the parameters R and f. The long filter F with f bits is divided into multiple segments of 96-bit to be sequentially transmitted in multiple tag slots [27]. Hence, the time for transmitting the filter is $\lceil \frac{f}{96} \rceil \times t_{tag}$. Therefore, the time cost of this round, denoted as $T_\triangle$, is $t_{tag} + \lceil \frac{f}{96} \rceil \times t_{tag}$. In this round, the average time $\frac{T_\triangle}{\aleph_1}$ for labeling an unknown tag is given as follows

$$\frac{T_\triangle}{\aleph_1} = \frac{t_{tag} + \lceil \frac{f}{96} \rceil \times t_{tag}}{M \times e^{-\frac{N}{f}}} \approx \frac{\frac{f}{96} \times t_{tag}}{M \times e^{-\frac{N}{f}}} \tag{2}$$

Note that, since the filter length f is normally very large [27], $t_{tag} + \lceil \frac{f}{96} \rceil \times t_{tag}$ is simplified to $\frac{f}{96} \times t_{tag}$

in Eq. (2). A smaller $\frac{T_{\triangle}}{\aleph_1}$ means a shorter time is consumed to label an unknown tag. Clearly, we need to minimize $\frac{T_{\triangle}}{\aleph_1}$ so as to get the best time-efficiency. Next, we will investigate the optimal filter length f that minimizes $\frac{T_{\triangle}}{\aleph_1}$. The derivative of $\frac{T_{\triangle}}{\aleph_1}$ is given as follows

$$\frac{\partial\, (\frac{T_{\triangle}}{\aleph_1})}{\partial\, f} = \frac{M \times e^{-\frac{N}{f}} \times \frac{t_{tag}}{96} \times (1 - \frac{N}{f})}{(M \times e^{-\frac{N}{f}})^2} \tag{3}$$

By setting the derivative $\frac{\partial\, (\frac{T_{\triangle}}{\aleph_1})}{\partial\, f}$ in Eq. (3) to 0, we obtain $f = N$. Moreover, when $f > N$, this derivative is larger than 0; when $f < N$, it is smaller than 0. Therefore, $\frac{T_{\triangle}}{\aleph_1}$ achieves the minimum value when the filter length f is set to N.

4.3 Determining the Minimum Round Count L_1

The unknown tags filtering process is repeated for multiple rounds and the round count is denoted as L_1. After L_1 rounds, the probability that a certain unknown tag can be labeled *at least once* is denoted as P, which can be given by

$$P = 1 - \prod_{k=1}^{L_1} (1 - P_k), \tag{4}$$

where P_k is the probability that this tag is labeled in the k^{th} round.

Since the filter length f is optimized to N in each round, P_k becomes a constant $\frac{1}{e}$. Then, we have

$$P = 1 - (1 - \frac{1}{e})^{L_1} \tag{5}$$

According to Eq. (5), each unknown tag has the independent probability P to be labeled at least once. So the ratio of unknown tags that can be labeled is also expected to be P. If the objective is to identify the unknown RFID tags with an accuracy of at least α, we should guarantee that the proportion P of unknown tags that can be labeled is no less than α. Then we have:

$$P = 1 - (1 - \frac{1}{e})^{L_1} \geq \alpha \tag{6}$$

By solving the above inequality, we get

$$L_1 \geq \frac{ln(1-\alpha)}{ln(1-e^{-1})} \tag{7}$$

That is, to identify the unknown RFID tags with a given accuracy α, the filtering process should be repeated for at least $\lceil \frac{ln(1-\alpha)}{ln(1-e^{-1})} \rceil$ rounds.

5 An Interactive Filtering-based Unknown Tag Identification Protocol

In the prior FUTI protocol, the *Unknown Tags Identification* phase is independent from the *Unknown Tags Filtering* phase. With a subtle modification to FUTI, we propose an Interactive Filtering-based Unknown Tag Identification (IFUTI) protocol, in which the interactive filters are used to not only label the unknown tags but also accelerate the identification of unknown tags.

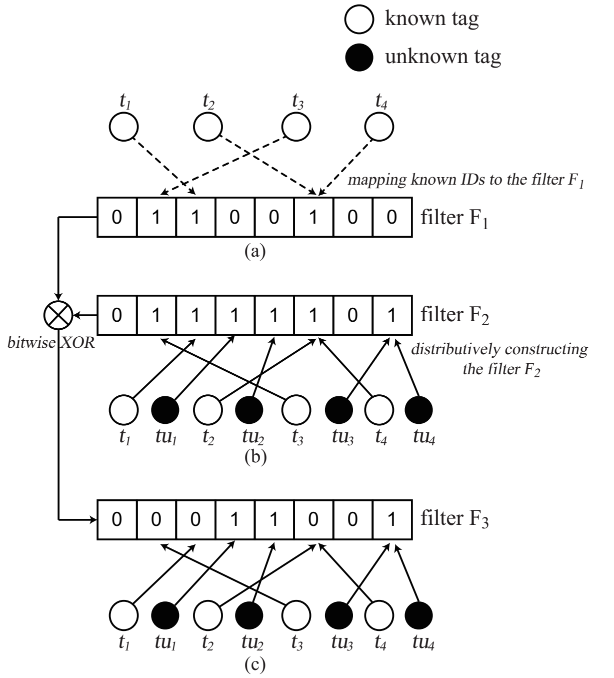


Fig. 3: Exemplifying the basic principle of the Interactive Filtering-based Unknown Tag Identification protocol.

5.1 Protocol Design

The IFUTI protocol also consists of two phases: (i) *Unknown Tags Filtering* phase; and (ii) *Unknown Tags Identification* phase. The detailed operations of these two phases are presented below.

5.1.1 Phase I: Unknown Tags Filtering

As illustrated in Fig. 3(a), the reader constructs a filter F_1 with f bits, by mapping all known IDs to it. The detailed procedures are the same as those in the FUTI protocol presented in Section 4.1.1. Clearly, '1s' in F_1 also indicate the locations of the known tags. The reader broadcasts the used parameters R and f to all the tags.

Since the *bit-level* synchronization between the reader and tags is achievable [34], [35], the tags are able to distributively construct another filter F_2 also with f bits by virtue of the synchronized physical layer transmissions. Specially, for an arbitrary tag, it creates a filter basis with f bits by setting the λ^{th} bit to '1', where $\lambda = H(ID, R) \mod f$; and setting all other $f-1$ bits to '0s'. All the tags simultaneously transmit their filter basis to the reader. In the physical layer, '0' is represented by an idle carrier; and '1' is represented by a busy carrier [34]. For each bit received by the reader, if the channel is idle, the bit is set to '0'; otherwise, if the channel is busy, this bit is set to '1'. After receiving all the filter basis, the reader is able to generate a global filter F_2 with f bits, as illustrated in Fig. 3 (b). Clearly, the known tags will select the same bits in F_1 and F_2 because the same parameters R and f are used. Therefore, if there is no unknown tag, the filter F_2 should be the same as the filter F_1.

When some unknown tags appear in the RFID system, some '0s' in the filter F_1 may become '1s' in the filter F_2. The difference between F_1 and F_2 indicate the appearance of unknown tags. As illustrated in Fig. 3 (c), we create the third filter $F_3 = F_2 \otimes F_1$, where $F_3[i] = 1$ if and only if $F_2[i] = 1$ AND $F_1[i] = 0$; otherwise, $F_3[i] = 0$, $i \in [0, f-1]$ based on bitwise *XOR* operation. Clearly, '1s' in the filter F_3 correspond to some unknown tags. The reader broadcasts the filter F_3 to all tags. Each tag checks the selected bit in the received filter F_3. If its representative bit is '1', it realizes its unknown identity and labels itself. The same as FUTI, a fraction of unknown tags could be labeled.

5.1.2 Phase II: Unknown Tags Identification

This unknown tag identification phase consists of two sub-stages: (i) The labeled unknown tags reply their IDs according to the order of '1s' in the filter F_3 [36]. As exemplified in Fig. 3 (c), the unknown tag tu_1 replies its ID in the first slot because its representative bit is the first '1' in the filter F_3. Similarly, the unknown tag tu_2 replies its ID in the second slot; the unknown tags tu_3 and tu_4 reply their IDs in the third slot. Some labeled unknown tags are able to successfully respond their IDs to the reader when the '1s' are exclusively occupied by them, e.g., tags tu_1 and tu_2. For the purpose of clarity, we refer to these unknown tags as $< 1-1 >$ unknown tags, where the former '1' indicates that they select '1s' in the filter F_3; the latter '1' indicates that they *exclusively* occupy their representative bits. (ii) Whereas, the other labeled unknown tags (e.g., tu_3 and tu_4) fail to reply their IDs to the reader due to the response collision, and will be identified by the classical EDFSA protocol. Similarly, we refer to them as $< 1-X >$ unknown tags, where 'X' indicates that more than one unknown tags share a common '1' in the filter F_3.

The labeled unknown tags are identified and will not participate in the next round. The proposed IFUTI protocol also repeats for multiple rounds until a fraction α of the unknown tags is expected to be labeled.

5.2 Determining the Optimal Filter Length f

In an arbitrary round, we first assume the number M^* of unidentified unknown tags is available to the reader. Clearly, in the first round, $M^* = M$. Later on we will discuss how to estimate the cardinality of the unidentified unknown tags at the beginning of each round. For a certain unidentified unknown tag, it could be labeled when it selects a '1' in the filter F_3. The corresponding probability, $P_{(1,*)}$, is given by

$$P_{(1,*)} = \binom{f}{1} \times \frac{1}{f} \times (1-\frac{1}{f})^N \approx e^{-\frac{N}{f}}, \qquad (8)$$

where f is the filter length and N is the number of known tags. We denote the probability that an arbitrary unknown tag exclusively occupies a '1' in the filter V_3 as $P_{(1,1)}$. Then, we have:

$$P_{(1,1)} = \binom{f}{1} \times \frac{1}{f} \times (1-\frac{1}{f})^{N+M^*-1} \approx e^{-\frac{N+M^*}{f}} \qquad (9)$$

Let $P_{(1,X)}$ denote the probability that an unknown tag shares a '1' in the filter F_3 with other tags. $P_{(1,X)}$ can be written as

$$P_{(1,X)} = P_{(1,*)} - P_{(1,1)} = e^{-\frac{N}{f}} - e^{-\frac{N+M^*}{f}} \qquad (10)$$

For a certain bit in the filer F_3, let $P_{'1'}$ denote the probability that this bit is '1'. The probability, $P_{'1'}$, is given by

$$P_{'1'} = (1-\frac{1}{f})^N \times [1-(1-\frac{1}{f})^{M^*}] \approx e^{-\frac{N}{f}}(1-e^{-\frac{M^*}{f}}) \qquad (11)$$

The total execution time of this round includes the transmission of filters F_2 and F_3 (both of them are of f bits), $f \times P_{'1'}$ tag slots (expectation) to identify the unknown tag IDs in the first sub-stage of Phase II and $e \times M^* \times P_{(1,X)}$ tag slots in the second sub-stage of Phase II to identify the labeled unknown tags that suffer from response collision. The execution time of this round, $T_\triangledown$, is given by

$$\begin{aligned} T_\triangledown =& \lceil \frac{2f}{96} \rceil \times t_{tag} + f \times P_{'1'} \times t_{tag} + e \times M^* \times P_{(1,X)} \times t_{tag} \\ \approx& \frac{2f}{96} \times t_{tag} + f \times [e^{-\frac{N}{f}}(1-e^{-\frac{M^*}{f}})] \times t_{tag} + \\ & e \times M^* \times (e^{-\frac{N}{f}} - e^{-\frac{N+M^*}{f}}) \times t_{tag} \end{aligned} \qquad (12)$$

In this round, we denote the number of identified unknown tags as $\aleph_2$, which is expected to be $M^* \times P_{(1,*)} \approx M^* \times e^{-\frac{N}{f}}$. Then, the average time for identifying an unknown tag is obtained as follows

$$\begin{aligned} \frac{T_\triangledown}{\aleph_2} &= \frac{\{\frac{2f}{96} + fe^{-\frac{N}{f}}(1-e^{-\frac{M^*}{f}}) + eM^*(e^{-\frac{N}{f}} - e^{-\frac{N+M^*}{f}})\}t_{tag}}{M^* e^{-\frac{N}{f}}} \\ &= \frac{[\frac{f}{48} + (f+eM^*)(e^{-\frac{N}{f}} - e^{-\frac{N+M^*}{f}})]t_{tag}}{M^* e^{-\frac{N}{f}}}, \end{aligned} \qquad (13)$$

which is a function with respect to only f when N and M^* is foreknown. It is easy to get the optimal filter length f_{op} to minimize the average time $\frac{T_\triangledown}{\aleph_2}$ in this round, e.g., exhaustively searching all the possible f (offline).

5.3 Determining the Minimum Round Count L_2

For an arbitrary unidentified unknown tag, the probability that it can be successfully identified in one round is equal to the ratio of '0s' in the filter F_1, which is available to the reader. The probability that an unknown tag is not identified after L_2 rounds is $\prod_{i=1}^{L_2}(1-\theta_{i0})$, where θ_{i0} is the ratio of '0s' in the filter F_1 of the i^{th} round. In other words, each tag has the probability $1-\prod_{i=1}^{L_2}(1-\theta_{i0})$ to be successfully identified after L_2

rounds. To achieve the given identification accuracy α, the repetition of the filtering-identification processes will not terminate until $1-\prod_{i=1}^{L_2}(1-\theta_{i0})>\alpha$.

5.4 Cardinality Estimation of the Unidentified Unknown Tags

Recall the analysis in Section 5.2; it is necessary to know the number M^* of the unidentified unknown tags to calculate the optimal filter length f in each round. Inspired by [37], the filter F_1 is used for estimating the cardinality of the unidentified unknown tags after the current round so as to facilitate the configuration of f in the next round. Obviously, the reader is able to know the number of unknown tags that are identified in this round, which is denoted as ξ. In this round, the actual filtering probability is equal to the ratio θ_0 of '0s' in the filter F_1, then the number of the left unlabeled (i.e., left unidentified) unknown tags is expected to be $\xi \times \frac{1-\theta_0}{\theta_0}$. That is, we use $\widehat{M^*}=\xi \times \frac{1-\theta_0}{\theta_0}$ as the estimator of the number of unknown tags that will participate in the next round. Then the filter length in the next round could be optimized accordingly. Since no filters are available before the first round, the cardinality estimation of the unknown tags participating in the first round should be treated separately. Fortunately, we can use the efficient cardinality estimation scheme ART proposed in [15] to estimate the cardinality of all the tags (i.e., $|\widehat{N+M}|$), then the cardinality M of the unknown tags at the very beginning is estimated as $|\widehat{N+M}|-N$, where N is the number of the known tags. Note that, except the first round, no extra overhead is introduced to estimate the cardinality of the unidentified unknown tags.

5.5 Discussion on the Multi-reader Case

Inspired by [15], we also leverage the approach proposed by Kodialam *et al.* in [10] to extend the proposed protocols to the multi-reader case. Specifically, we uses a central controller to synchronize all readers. In the proposed protocols, the involved parameters R, f and the constructed filter have the same value across all readers. Furthermore, each reader sends the received data to the central controller. That is, the multiple synchronized readers are logically treated as one. Using this simple method, the proposed protocols are able to work in the multi-reader scenarios.

6 Performance Evaluation

The problem addressed in this paper is to identify the unknown tags in a time-efficient way. In this section, we evaluate the performance of the proposed FUTI and IFUTI protocols. First, extensive simulation experiments are conducted to compare our protocols against the state-of-the-art protocols in the current literature [12], [25] in terms of time-efficiency. Second, another set of experiments are preformed to validate the identification accuracy of FUTI and IFUTI, respectively. The simulators were implemented via MATLAB on a ThinkPad X230 desktop with an Intel i5 3230M CPU and 8G RAM. Compared with the delay of wireless data transmission, the time consumed by computing on both the reader side and the tag side is so minor, and thus is neglected. Therefore, we only consider the time consumed by the wireless communications between the reader and the tags. The same as [12], [25], we consider the single reader case and assume the communication channel is error-free. Each simulation was conducted for 1000 times and then we recorded the averaged results of the 1000 independent trials.

6.1 Total Execution Time

In this subsection, we evaluate the total execution time of the proposed FUTI and IFUTI protocols. Actually, the authors in [25] proposed a series of protocols to identify the unknown RFID tags, including Basic Unknown tag Identification Protocol (BUIP), BUIP with Collision-Empty Slot Pairing (BUIP-CE) and BUIP with Collision-Fresh Slot Paring (BUIP-CF). Hence, in this subsection, we compare the proposed protocols with CU [12], BUIP, BUIP-CE and BUIP-CF [25].

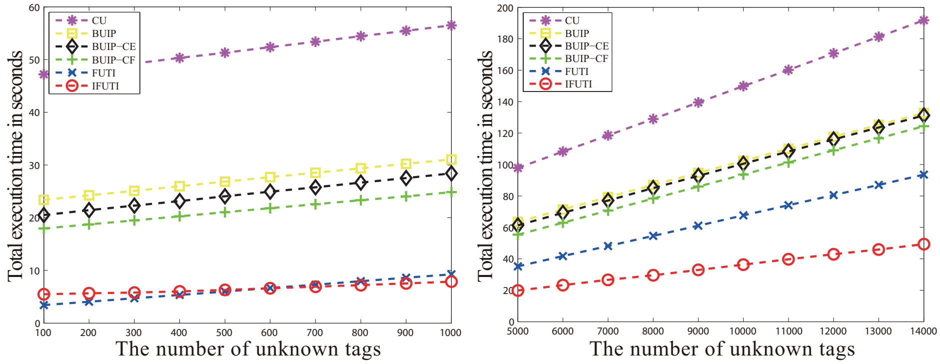
In the simulation experiments, identification accuracy α is predefined to 99%, and the number N of known tags is fixed to $10,000$. In different applications, the cardinality of the unknown tags may be different. In order to fully evaluate the performance of the proposed protocols, we conducted two sets of simulations with *different densities of unknown tags*.

6.1.1 Low Density of Unknown Tags

Here, we simulate an RFID system with a low density of unknown tags, where the number M of unknown tags varies from 100 to 1000 with a step of 100. The simulation results in Fig. 4 (a) demonstrate that the proposed FUTI and IFUTI protocols considerably outperform all the existing advanced protocols in [12], [25]. For example, the execution time of BUIP-CF and CU is $18.7s$ and $48.2s$, respectively, when the number M of unknown tags is 200. And the the execution time of the proposed FUTI protocol is just $4.1s$, representing reduction of 78.1% and 91.5% when compared to the BUIP-CF and CU protocols, respectively. At the same time, the execution time of the proposed IFUTI protocol is $5.7s$, indicating reduction of 69.5% and 88.2% when compared to the benchmark protocols.

6.1.2 High Density of Unknown Tags

In this set of simulation experiments, we evaluate the performance of the proposed protocols in an RFID system with a high density of unknown tags, where the number M of unknown tags varies from 5000 to $14,000$ with a step of 1000. The simulation results



(a) low density of unknown tags (b) high density of unknown tags

Fig. 4: Evaluating the execution time of the proposed protocols, where the number N of known tags is fixed to $10,000$; and the identification accuracy α is predefined as 99%.

shown in Fig. 4 (b) demonstrate that the proposed FUTI and IFUTI protocols also perform better than the protocols in [25], [12] in an RFID system with high density of unknown tags. For example, when $M = 12,000$, the execution time of BUIP-CF and CU is $109.0s$ and $170.7s$, respectively. And the the execution time of the proposed FUTI protocol is $80.6s$, representing the reduction of 26.1% and 52.6% when compared to the BUIP-CF and CU protocols, respectively. On the other hand, the execution time of the proposed IFUTI protocol is just $43.0s$, which outperforms BUIP-CF and CU by reducing 60.6% and 74.8% of the required execution time.

The results shown in Fig. 4 (a) and (b) also reveal that the FUTI protocol is more efficient for the RFID systems with low density of unknown tags; and the IFUTI protocol is more suitable for the RFID systems with high density of unknown tags, which matches the analysis presented in Section 1.4.

6.2 Identification Accuracy

Another important performance metric of the proposed protocols that needs to be evaluated is the actual identification accuracy. In this subsection, we conduct simulation experiments under different parameters (i.e., M and α) to evaluate the identification accuracy of the proposed FUTI and IFUTI protocols, respectively. The two set of simulation results shown in Figs. 5 and 6 demonstrate that the proposed protocols could satisfy the the given identification accuracy. As illustrated in Fig. 5 (a), the actual identification accuracy of FUTI is 99.4% when the number M of the unknown tags is 500, which is higher than the given accuracy $\alpha = 99\%$. Similarly, as shown in Fig. 6 (d), the actual identification accuracy of IFUTI is 96.9%, when $M = 10,000$, which is higher than the predefined accuracy $\alpha = 95\%$.

7 Conclusion

This paper studies the important problem of unknown tag identification in large-scale RFID systems. Specifically, we aim at identifying the unknown tags with a given accuracy. The solutions to this problem are desirable in many practical applications, such as identifying the unknown items which are misplaced in the scanning area. This paper first investigates a cost-effective filter to label the unknown tags at the bit-level, and thus proposes a Filtering-based Unknown Tag Identification (FUTI) protocol. Based on FUTI, we investigate interactive filters to not only label the unknown tags but also accelerate the identification of the labeled unknown tags, and thus propose an Interactive Unknown Tag Identification (IFUTI) protocol. We also present the theoretical analysis of the protocol parameters to minimize the execution time of the proposed protocols. Furthermore, extensive simulation experiments are conducted to evaluate the performance of the proposed protocols and the results demonstrate that the proposed protocols considerably outperforms the existing advanced protocols. In this paper, we assume the communication channel is error-free. In our future work, we will conduct real experiments to investigate the impact of channel error on the proposed protocols.

Acknowledgments

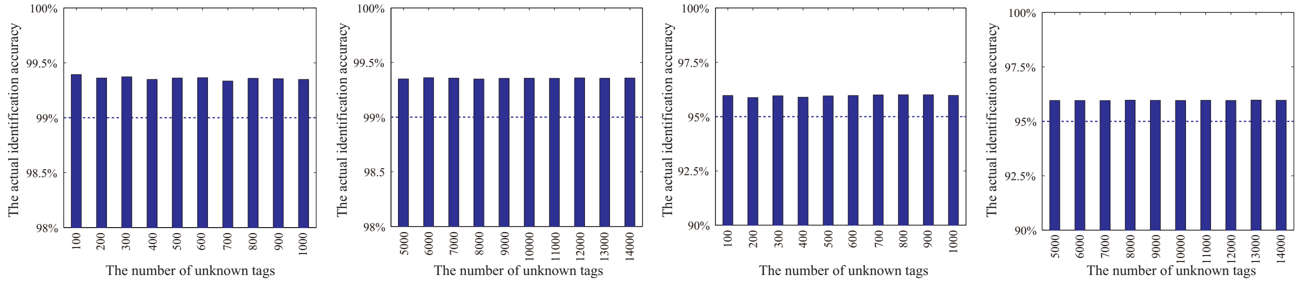
This work was supported by NSFC (Grant No.s 60973117, 61173160, 61173162, and 60903154), New Century Excellent Talents in University (NCET) of Ministry of Education of China, and the National Science Foundation for Distinguished Young Scholars of China (Grant No. 61225010).

References

[1] L. M. Ni, Y. Liu, Y. C. Lau, and A. P. Patil, "Landmarc: Indoor Location Sensing Using Active RFID," *Wireless networks*, vol. 10, no. 6, pp. 701–710, 2004.

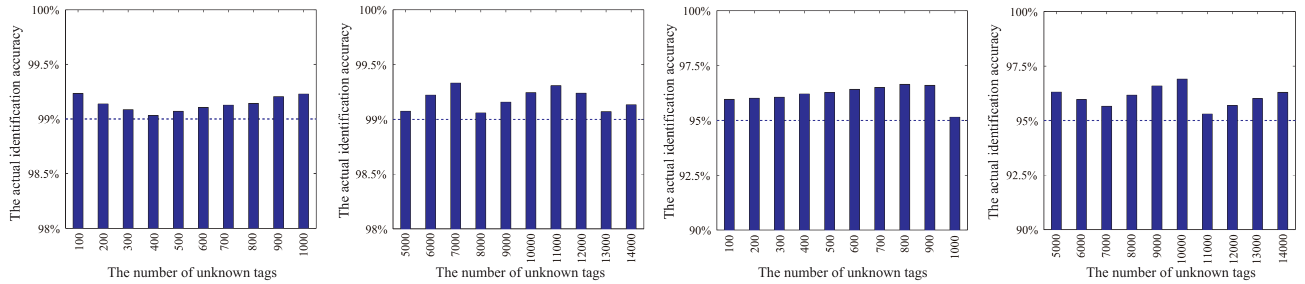
[2] C. Wang, H. Wu, and N.-F. Tzeng, "RFID-Based 3-D Positioning Schemes," *Proc. of IEEE INFOCOM*, pp. 1235–1243, 2007.

[3] A. Matic, A. Papliatseyeu, V. Osmani, and O. Mayora-Ibarra, "Tuning to Your Position: FM radio based Indoor Localization with Spontaneous Recalibration," *Proc. of IEEE PerCom*, pp. 153–161, 2010.



(a) FUTI (99%)-low density of unknown tags (b) FUTI (99%)-high density of unknown tags (c) FUTI (95%)-low density of unknown tags (d) FUTI (95%)-high density of unknown tags

Fig. 5: Evaluating the actual identification accuracy of the proposed FUTI protocol, where the number N of known tags is set to $10,000$.



(a) IFUTI (99%)-low density of unknown tags (b) IFUTI (99%)-high density of unknown tags (c) IFUTI (95%)-low density of unknown tags (d) IFUTI (95%)-low density of unknown tags

Fig. 6: Evaluating the actual identification accuracy of the proposed IFUTI protocol, where the number N of known tags is set to $10,000$.

[4] W. Cheng, X. Cheng, M. Song, B. Chen, and W. W. Zhao, "On the Design and Deployment of RFID Assisted Navigation Systems for VANETs." *IEEE Transactions on Parallel and Distributed Systems*, vol. 23, no. 7, pp. 1267–1274, 2012.

[5] L. Xie, B. Sheng, C. C. Tan, H. Han, Q. Li, and D. Chen, "Efficient Tag Identification in Mobile RFID Systems," *Proc. of IEEE INFOCOM*, pp. 1–9, 2010.

[6] B. Sheng, C. C. Tan, Q. Li, and W. Mao, "Finding Popular Categories for RFID Tags," *Proc. of ACM MobiHoc*, pp. 159–168, 2008.

[7] C. Lee and C. Chung, "Efficient Storage Scheme and Query Processing for Supply Chain Management using RFID," *Proc. of ACM SIGMOD*, pp. 291–302, 2008.

[8] S. Chen, M. Zhang, and B. Xiao, "Efficient Information Collection Protocols for Sensor-augmented RFID Networks," *Proc. of IEEE INFOCOM*, pp. 3101–3109, 2011.

[9] C. Qian, H. Ngan, Y. Liu, and L. M. Ni, "Cardinality Estimation for Large-Scale RFID Systems," *IEEE Transactions on Parallel and Distributed Systems*, vol. 22, no. 9, pp. 1441–1454, 2011.

[10] M. Kodialam, T. Nandagopal, and W. C. Lau, "Anonymous Tracking using RFID tags," *Proc. of IEEE INFOCOM*, pp. 1217–1225, 2007.

[11] C. C. Tan, B. Sheng, and Q. Li, "Efficient Techniques for Monitoring Missing RFID Tags," *IEEE Transactions on Wireless Communications*, vol. 9, no. 6, pp. 1882–1889, 2010.

[12] B. Sheng, Q. Li, and W. Mao, "Efficient Continuous Scanning in RFID systems," *Proc. of IEEE INFOCOM*, pp. 1–9, 2010.

[13] K. Bu, B. Xiao, Q. Xiao, and S. Chen, "Efficient Pinpointing of Misplaced Tags in large RFID Systems," *IEEE Transactions on Parallel and Distributed Systems*, vol. 23, no. 11, pp. 2094–2106, 2012.

[14] W. Luo, S. Chen, T. Li, and S. Chen, "Efficient Missing Tag Detection in RFID Systems," *Proc. of IEEE INFOCOM*, pp. 356–360, 2011.

[15] M. Shahzad and A. Liu, "Every Bit Counts-Fast and Scalable RFID Estimation," *Proc. of ACM MOBICOM*, pp. 365–376, 2012.

[16] R. Ananth, D. Nicole, and T. Zeynep, "Execution: The missing link in retail operations," *California Management Review*, vol. 43, no. 3, pp. 136–152, 2001.

[17] Y. Yin, L. Xie, S. Lu, and D. Chen, "Efficient protocols for rule checking in rfid systems," *Proc. of IEEE ICCCN*, pp. 1–7, 2013.

[18] S. Lee, S. Joo, and C. Lee, "An Enhanced Dynamic Framed Slotted ALOHA Algorithm for RFID Tag Identification," *Proc. of IEEE MobiQuitous*, pp. 166–172, 2005.

[19] F. C. Schoute, "Dynamic Frame Length ALOHA," *IEEE Transactions on Communications*, vol. 31, no. 4, pp. 565 – 568, 1983.

[20] L. G. Roberts, "Aloha Packet System with and without Slots and capture," *ACM SIGCOMM Computer Communication Review*, vol. 5, no. 2, pp. 28–42, 1975.

[21] J. Myung and W. Lee, "Adaptive Splitting Protocols for RFID Tag Collision Arbitration," *Proc. of ACM MobiHoc*, pp. 202–213, 2006.

[22] N. Bhandari, A. Sahoo, and S. Iyer, "Intelligent Query Tree (IQT) Protocol to Improve RFID Tag Read Efficiency," *Proc. of IEEE ICIT*, pp. 46–51, 2006.

[23] V. Namboodiri and L. Gao, "Energy-Aware Tag Anticollision Protocols for RFID Systems," *IEEE Transactions on Mobile Computing*, vol. 9, no. 1, pp. 44–59, 2010.

[24] M. Shahzad and A. X. Liu, "Probabilistic Optimal Tree Hopping for RFID Identification," *Proc. of ACM SIGMETRICS*, pp. 293–304, 2013.

[25] X. Liu, S. Zhang, K. Bu, and B. Xiao, "Complete and Fast Unknown Tag Identification in Large RFID Systems," *Proc. of IEEE MASS*, pp. 47–55, 2012.

[26] W. Luo, S. Chen, T. Li, and Y. Qian, "Probabilistic Missing-tag Detection and Energy-Time Tradeoff in Large-scale RFID systems," *Proc. of ACM MobiHoc*, pp. 95–104, 2012.

[27] T. Li, S. Chen, and Y. Ling, "Identifying the Missing Tags in a Large RFID System," *Proc. of ACM MobiHoc*, pp. 1–10, 2010.

[28] R. Zhang, Y. Liu, Y. Zhang, and J. Sun, "Fast Identification of the Missing Tags in a Large RFID System," *Proc. of IEEE SECON*, pp. 278–286, 2011.

[29] Y. Zheng and M. Li, "P-mti: Physical-layer missing tag identification via compressive sensing," *Proc. of IEEE INFOCOM*, pp. 917–925, 2013.

[30] H. Han, B. Sheng, C. C. Tan, Q. Li, W. Mao, and S. Lu, "Counting RFID Tags Efficiently and Anonymously," *Proc. of IEEE INFOCOM*, pp. 1–9, 2010.

[31] P. Semiconductors, "I-CODE Smart Label RFID Tags," *http://www.nxp.com/acrobat_download/other/identification/SL 092030.pdf*, Jan 2004.

[32] W. Luo, S. Chen, T. Li, and Y. Qiao, "Probabilistic Missing-

tag Detection and Energy-Time Tradeoff in Large-scale RFID Systems," *Proc. of ACM MobiHoc*, pp. 95–104, 2012.
[33] X. Liu, K. Li, Y. Shen, G. Min, B. Xiao, W. Qu, and H. Li, "A Fast Approach to Unknown Tag Identification in Large Scale RFID Systems," *Proc. of IEEE ICCCN*, pp. 1–7, 2013.
[34] H. Yue, C. Zhang, M. Pan, Y. Fang, and S. Chen, "A Time-efficient Information Collection Protocol for Large-scale RFID Systems," *Proc. of IEEE INFOCOM*, pp. 2158–2166, 2012.
[35] J. W. H. H. D. K. P. Indyk, "Efficient and Reliable Low-Power Backscatter Networks," *Proc. of ACM SIGCOMM*, vol. 42, no. 4, pp. 61–72, 2012.
[36] Y. Qiao, S. Chen, T. Li, and S. Chen, "Energy-efficient Polling Protocols in RFID Systems," *Proc. of ACM MobiHoc*, 2011.
[37] M. Chen, W. Luo, Z. Mo, S. Chen, and Y. Fang, "An efficient tag search protocol in large-scale rfid systems," *Proc. of IEEE INFOCOM*, 2013.

Xiulong Liu received the B.E. degree from the School of Software Technology, Dalian University of Technology, China, in 2010. Currently, he is a Ph.D. candidate in the School of Computer Science and Technology, Dalian University of Technology, China. His research interests include RFID systems and wireless sensor networks.

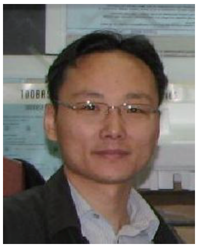
Keqiu Li received the bachelor's and master's degrees from the Department of Applied Mathematics at the Dalian University of Technology in 1994 and 1997, respectively. He received the Ph.D. degree from the Graduate School of Information Science, Japan Advanced Institute of Science and Technology in 2005. He also has two-year postdoctoral experience in the University of Tokyo, Japan. He is currently a professor in the School of Computer Science and Technology, Dalian University of Technology, China. He has published more than 100 technical papers, such as IEEE TPDS, ACM TOIT, and ACM TOMCCAP. He is an Associate Editor of IEEE TPDS and IEEE TC. He is a senior member of IEEE. His research interests include internet technology, data center networks, cloud computing and wireless networks.

Geyong Min is a Professor of High Performance Computing and Networking in the Department of Mathematics and Computer Science within the College of Engineering, Mathematics and Physical Sciences at the University of Exeter, United Kingdom. He received the PhD degree in Computing Science from the University of Glasgow, United Kingdom, in 2003, and the B.Sc. degree in Computer Science from Huazhong University of Science and Technology, China, in 1995. His research interests include Next Generation Internet, Wireless Communications, Multimedia Systems, Information Security, Ubiquitous Computing, Modelling and Performance Engineering. His recent research has been supported by UK EPSRC, Royal Society, Nuffield Foundation, and European FP. Prof. Min has published over 200 research papers in prestigious international journals, including IEEE Transactions on Computers, IEEE Transactions on Parallel and Distributed Systems, IEEE Transactions on Communications, IEEE Transactions on Wireless Communications, and IEEE Transactions on Multimedia, and in reputable international conferences, such as ICDCS, IPDPS, GLOBECOM, and ICC. He is an Editorial Board member of 9 international journals. He served as the Guest Editor for 17 International Journals and was the Chair or Vice-Chair of 30 international conferences/workshops. He was awarded the Outstanding Leadership Awards from IEEE International conferences CIT'2010/ScalCom'2010/ICESS'2010, ScalCom'2009, HPCC'2008.

Kai Lin received the doctoral degree in computer science, the masters degree from Northeastern University, and the bachelors degree from Dalian University of Technology. He is an assistant professor at the School of Computer Science and Engineering, Dalian University of Technology. He currently serves on the Editorial Boards of three peer-reviewed international journals. He has served as the general chair, technical program committee chair, and symposium chair for many international conferences. His research interests include wireless networks, ubiquitous computing, mobile computing, and system security.

Bin Xiao received the B.Sc. and M.Sc. degrees in electronics engineering from Fudan University, China, in 1997 and 2000, respectively, and the Ph.D. degree in computer science from the University of Texas at Dallas in 2003. After his Ph.D. graduation, he joined the Hong Kong Polytechnic University as an assistant professor. Currently, he is an associate professor in the Department of Computing at The Hong Kong Polytechnic University, Hong Kong. His research interests include mobile cloud computing, data management, network security, wireless sensor networks, and RFID systems. He is an associate editor for the International Journal of Parallel, Emergent and Distributed Systems.

Dr. Xiao is a recipient of the Best Paper Award from IEEE/IFIP EUC 2011.



Yanming Shen received the B.S degree in automation from Tsinghua University, Beijing, China, in 2000, and the Ph.D. degree from the Department of Electrical and Computer Engineering at the Polytechnic Institute of New York University, Brooklyn, in 2007. He is a Professor with the School of Computer Science and Technology, Dalian University of Technology, DaLian, China. His general research interests include packet switch design, data center networks, peer-to-peer video streaming, and algorithm design, analysis, and optimization. He is a recipient of the 2011 Best Paper Awards for Multimedia Communications (awarded by IEEE Communications Society).

Weyu Qu received the bachelor's and master's degrees from Dalian University of Technology, China in 1994 and 1997, and the doctorate degree from Japan Advanced Institute of Science and Technology in 2006. She is a professor at the School of Information and Technology, Dalian Maritime University, China. She was a lecturer in Dalian University of Technology from 1997 to 2003. Her research interests include mobile agent-based technology, distributed computing, computer networks, and grid computing. She has published more than 50 technical papers in international journals and conferences. She is on the committee board for a couple of international conferences.