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Efficient Physical-layer Unknown Tag Identification in Large-scale RFID Systems

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***Abstract*—Radio Frequency Identification (RFID) is an automatic identification technology that brings a revolutionary change to quickly identify tagged objects from the collected tag IDs. Considering the misplaced and newly added tags, fast identifying such unknown tags is of paramount importance, especially in large-scale RFID systems. Existing solutions can either identify all unknown tags with low time-efficiency, or identify most unknown tags quickly by sacrificing the identification accuracy. Unlike existing work, this paper proposes a protocol that utilizes physical layer (PHY) information to identify the intact unknown tag set with high efficiency. We exploit the physical signals in collision slots to separate unknown tags from known tags, a new technique to speed up the ID collection. Such new technique was verified in a RFID prototype system using the USRP-based reader and WISP tags. We also evaluated our protocol to show the efficiency of leveraging PHY signals to successfully get all unknown tag IDs without wasted known tag ID transmission. Simulation results show that our protocols outperform prior unknown tag identification protocols. For example, given 1,000 unknown tags and 10,000 known tags, our best protocol has 56.8% less time to the state-of-the-art protocol when collecting all unknown tag IDs.**

***Index Terms*—RFID system, unknown tag identification, time efficiency, physical layer.**

I. Introduction

Radio Frequency Identification (RFID) is an automatic identification technology that brings a revolutionary change in a range of applications, such as manufacturing [2]–[4], cargo tracking [5]–[9], logistics [10], [11] and warehouse management [12]–[14]. In these applications, unknown tag identification is essential to successfully collect tag IDs from newly added tags. For instance, with a batch of tagged items being transported into a warehouse or supermarket like Walmart, all new tag IDs are supposed to be stored into the backend server for further business operation, such as daily inventory. However, considering a large RFID system with tens of thousands of known tags whose IDs have been stored previously, it is challenging to fast identify unknown tags since these known tags will participate in the identification.

An intuitive way to identify unknown tags is that the reader inventories all known and unknown tags together and then compares the collected tags with previous stored tags in the database. This kind of approach is straightforward but takes unnecessary time to identify known tags, dramatically decreasing the identification performance. Considering whether identifying the intact unknown set or not, existing work on unknown tag identification falls into two categories: *probabilistic identification* and *deterministic identification*. The probabilistic identification can efficiently identify the unknown tags with a desired accuracy (e.g. over 95%) [15]. The deterministic identification can definitely identify all unknown tags without missing anyone [16].

Probabilistic identification improves the identification efficiency but sacrifices the identification accuracy. The state-of-the-art probabilistic protocol, IFUTI [15], investigates interactive vectors to label the unknown tags and accelerate the identification of the labeled unknown tags. In the first filtration phase, a fraction of unknown tags are supposed to be labeled. Then in the second collection phase, the reader gathers the IDs of labeled unknown tags without interference from known tags. IFUTI generally outperforms the existing advanced protocols [16]. However, it is unable to collect the entire unknown tags.

Deterministic identification can collect all unknown tag identifiers, but usually tends to be time-consuming. Consider the most efficient deterministic tag identification protocol called BUIP-CF [16]. The reader first broadcasts an indicator vector and the tags reply according to it. The reader distinguishes unknown tags from known tags using response information and known tags are deactivated in the later inventory. After this, the reader queries the remaining active tags, i.e. all unknown tags. BUIP-CF improves the efficiency of prior work with identifying the intact unknown tag set. However BUIP-CF consumes extra time to separate tags without utilizing collision slot.

This paper aims to design a time-efficient deterministic identification protocol that can gather the entire unknown tag IDs as well as achieve high identification efficiency. We propose an efficient Physical-layer Unknown Tag Identification (PUTI) protocol. PUTI dives into physical layer to extract useful information from collision slots, instead of focusing on individual tag responses, which makes a fundamental improvement on the performance. As a deterministic identification protocol, PUTI consists of two phases. In the first phase, the reader separates unknown tags from known tags by checking the state of each slot. The noticeable advantage is that our protocols take full use of not only empty slots, but also singleton slots and collision slots by further mining physical layer signals, which greatly reduces the execution time of filtering the known tags. Additionally, our protocol can

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definitely filter all unknown tags without missing any ones. In the second phase, PUTI identifies the intact unknown tag set using ID collection scheme. At the end of two phases, the system can access the IDs of entire unknown tags. We also theoretically analyze the protocol performance by giving the optimal frame size setting and impact of unknown tag ratios.

We implement a prototype system and validate our design based on the Universal Software Radio Peripheral (USRP) platform and the Intel Wireless Identification and Sensing Platform (WISP). Furthermore we conduct extensive simulations to evaluate our protocol performance. The simulation results demonstrate that our protocols are faster than the state-of-the-art identification protocols, including both deterministic identification and probabilistic identification. For example, given a RFID system with 1,000 unknown tags and 10,000 known tags, our best protocol PUTI outperforms BUIP-CF by reducing 56.8% of the required execution time.

The rest of this paper is organized as follows. We briefly introduce the related work in Section II. Section III introduces the background of unknown tag identification problem, including system model and problem description. Section IV introduces the technique for utilizing PHY signal constellations to explore the slot state. We propose our protocol PUTI, and give the analysis of the protocol efficiency in Section V. Section VI evaluates the protocol performance via simulations. Finally, Section VII concludes this paper.

II. Related Work

Existing tag identification protocols fall into two categories: Tree-based protocols [17] and Aloha-based protocols [18], [19]. In Tree-based protocols, a dynamic ID prefix of tag IDs is applied to progressively split a tag set into ever smaller subsets until only one tag is left in each subset. The reader sends an initialization request and then transmits one bit of ID data at a time. The reader iteratively splits the tags in its interrogation region into two groups. Then the reader sends command to tags to poll the each group. If there exists collisions, the reader divides the another two groups. Tags with matching bits will reply. Only until at least one of groups contains one tag, the reader can identify the tag. In Aloha-based identification protocols, each tag randomly selects a slot and only the slots chosen by exactly one tag can be used to collect ID information. The reader broadcasts an initialization command and a parameter that the tags individually use to reply in a random slot. A frame consists of a number of slots, which is divided into a time interval between requests of a reader. When receiving the request, each tag transmits its ID in the corresponding slot. While the identification protocols can be adopted to address the tag distribution problem, it does not make use of the prior knowledge of all tag IDs, leading to inefficient tag distribution exploring processes.

The problem of fast unknown tag identification is very important and has attracted quite a lot of research efforts. To the best of our knowledge, CU [20] first demonstrated the problem of the unknown tag identification. It can collect a specified fraction of the intact unknown tags. Since the solution is based on randomized algorithms, CU cannot guarantees perfect accuracy of identifying unknown tags. Considering whether identifying the intact unknown set, existing work on unknown tag identification falls into two categories: deterministic identification and probabilistic identification. For deterministic identification of unknown tags, Liu *et al* proposed BUIP-CF [16]. The reader distinguishes known tags from unknown tags by comparing the expected replies of known tags with actual replies of tags. Until all the known tags are deactivated, the reader collects the rest unknown tags. Although BUIP-CF improves the efficiency of prior work with identifying the intact unknown tag set, it is usually time-consuming. As the state-of-the-art probabilistic protocol, Liu *et al* proposed IFUTI [15] to identify the unknown tags with a desired accuracy in a fast way. The reader investigates interactive vectors to label the unknown tags and accelerates the identification of the labeled unknown tags. When unknown tags are labeled with expected accuracy, the reader gathers the IDs of labeled unknown tags without interference from known tags. IFUTI generally outperforms the existing advanced protocols. However, it is unable to collect the entire unknown tags.

This paper proposes PUTI that gathers the entire unknown tag IDs as well as achieve high identification efficiency. The reader separates the unknown tags from known tags by checking the state of each slot. Additionally, they can also definitely filter all unknown tags without missing any ones.

III. Preliminary

A. System Model

We consider a large-scale RFID system with a reader, a massive number of tags and a back-end server. The tags attached to items are under the surveillance region covered by the reader. After communicating with the tags, the reader transmits tag information to a back-end server, which provides powerful computation ability to process such data. The back-end server connects the reader via wired or wireless links, and sends orders to schedule working. The server also stores all IDs of the known tags. As the new tagged objects move in, the unknown tags will also exist in the system.

Similar to prior work [21], [22], the communication mode between tags and the reader is slotted frame. The tag talks only if receiving the reader's commands. A reader initializes each round of our protocol by sending a request. On receiving the order, tags then backscatter signals. The reader initiates the communication with a high power continuous wave (CW) which energizes RFID tags. By utilizing the backscatter modulation, the tag is able to transmit information to the reader. But in a slot, there will be more than one tag replies, which leads to signal collision. Due to the constraints of transmission power, the communication bandwidth is generally narrow and thus can be mathematically modeled using a single complex number [23]. Thus, the reader is able to calculate the state of each slot.

The protocols proposed in this paper can also be applied to RFID systems containing multiple readers. In such cases, the reader collision will occur when two or more readers attempt to communicate with a tag concurrently, since the mixed signals cannot be correctly decoded at the tag side. Many existing reader-collision against schemes [24], [25] have been proposed to achieve dynamical reader schedule. We can resort to these works to avoid the communication collision among multiple readers. When multiple readers are synchronized, we can logically treat them as a whole. As the same with [15], [16], we regard the multiple readers as a single one in this paper.

B. Problem Description

Consider a large-scale RFID system with both known tags and unknown tags. We denote the set of known tags as N and the set of unknown tags as M. The tags in N differ from those in M which is $N \cap M = \varnothing$. The symbols n and m depict the number of tags in N and M, respectively. But the back-end server only stores the known tag IDs N in the database, which means the IDs from unknown tag set M are new to the server. Therefore, our problem is how to fast identify all m unknown tags in such RFID system.

An intuitive way to identify unknown tags is that the reader inventories all known and unknown tags in $N \cup M$ together. Then the reader compares the collected tags $N \cup M$ with previous stored tags in the database, that is $N \cup M - N = M$. This kind of approach is straightforward but takes unnecessary time to identify known tags, dramatically decreasing the identification performance, especially when n is large. Therefore, in order to identify all the unknown tags quickly, we strive to achieve the identification efficiency by fast separating m unknown tags from n known tags.

IV. PHY Signal Constellations

A. Background

The communications between the readers and tags follow the Reader-Talk-First model. Namely, the tag talks only if receiving the reader's commands. A reader initializes each round by sending a request. On receiving the order, each tag randomly chooses a slot. In passive RFID systems, the communications is half-duplex, the reader would not modulate any signal, but only use continuous carrier transmission to provide energy for the RFID tags. By utilizing the backscatter modulation, the tag is able to transmit information to the reader. But in a slot, there will be more than one tag replies, which leads to signal collision. By cascading a low-pass filter, the reader can recover the base-band signal. Due to the constraints of transmission power, the communication bandwidth is generally narrow and thus can be mathematically modeled using a single complex number.

We denote K is the total number of tags reply in a slot, indexed by i. Therefore, the low-pass equivalent symbol can be represented as a complex number which consists amplitude and phase components as follows:

$$s(t) = \sum_{i=1}^{K} h_i a_i(t) + L + n(t), \tag{1}$$

where

$$\begin{aligned} h_i &= h_i^f h_i^b \sqrt{\Delta\sigma_i}, \\ a_i(t) &= \sum_k d_{k,i} p(t,k). \end{aligned} \tag{2}$$

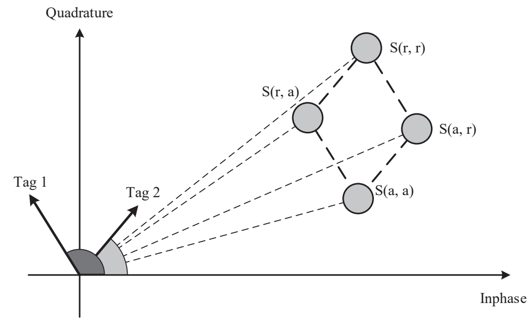


Fig. 1. Mapping two collided tag signals to an IQ plane.

Here, h_i is a flat fading linear time invariant channel in a very short time, in which h_i^f and h_i^b are the forward (reader to tag) and the backward (tag to reader) channel attenuation, respectively. $\Delta\sigma_i$ is the normalised differential radar cross section as described by [26]. $a_i(t)$ is realises an on-off keying, in which $d_{k,i}$ is the transmitted symbol ($d_{k,i} \in \{0, 1\}$) and $p(t, k)$ is the pulse shape of the modulation signal. Note, while the RFID tags absorb energy from the field the carrier transmission will leak into the receive paths of the RFID reader. We denote this carrier leakage at receive antenna as L. $n(t)$ denotes the complex-valued noise at antenna, with zero mean.

Then we can easily maps the signals in the baseband I/Q plane. Due to a single source, the carrier frequency of all signal components modulated is the same. While a tag absorb energy, the reader only can discover the carrier leakage, i.e., the absorb state as

$$s^{(a)} = L. \tag{3}$$

While a tag backscatters information to the reader, the reader can discover the reflect state of tag i as

$$s^{(r)} = h_i + L. \tag{4}$$

When two tag backscatters (tag i and j) in a slot, the reader will possible discover four states as follows:

$$\begin{aligned} s^{(a,a)} &= L, \\ s^{(r,a)} &= h_i + L, \\ s^{(a,r)} &= h_j + L, \\ s^{(r,r)} &= h_i + h_j + L. \end{aligned} \tag{5}$$

Then we plot the collided signals to I/Q plane, as shown in Fig. 1. The location of the constellation in the I/Q plane depends on the value of the carrier leakage and on the channel coefficients.

Therefore, the total number of different states shown in the I/Q plane indicates the number of tags selecting the current slot. Each tag takes one of the two states by either reflecting or absorbing radio waves from the reader, the exact number of concurrent tag responses in a slot can be detected. If there are K tags in a slot, the reader would discover 2^N possible combinations. We will take this feature in designing our protocol PUTI. This counting process does not need bit synchronization. Instead, some misalignment of each tag reply

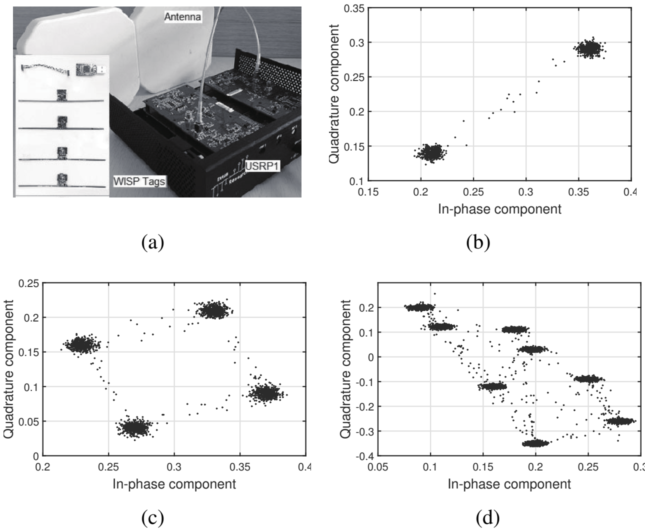


Fig. 2. Implementation of symbol clustering. (a) Platform: USRP1 with two complete RFX900 daughterboards and the WISP tags. (b) 1 tag, 2 clusters. (c) 2 tags, 4 clusters. (d) 3 tags, 8 clusters.

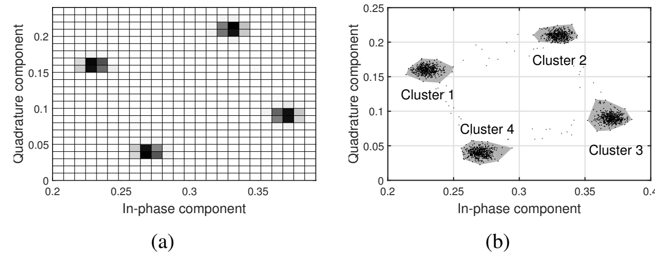


Fig. 3. An example case of our symbol clustering algorithm for 2 tags. (a) Pre-processing phase. (b) Clustering phase.

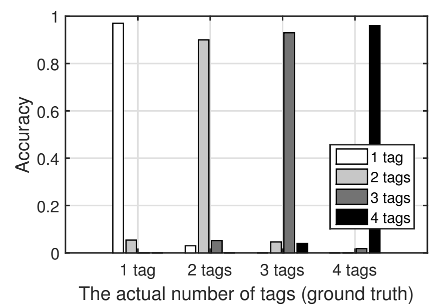


Fig. 4. Accuracy performance of the clustering algorithm

can have more clear symbol clusters, which is robust to imperfect clock synchronization.

Although the reader can extract the number of concurrent tag responses in the slot, but in the actual environment, the parameter will impact on the accuracy of identification of the number. When increasing the number of tags in a slot, the performance using this method degrades. Because the clusters in the I/Q plane will be closer to each other, when the number of clusters increase, which impacts the accuracy.

B. *Implementation of Symbol Clustering*

To explore the efficiency of symbol clustering in actual environment, we setup a testbed with USRP software-defined platform and programmable WISP tags. Our test environment is shown in Fig. 2(a). USRP1 in the prototype has two complete RFX900 daughterboards which are designed for operation in the 900 MHz band. The RFID tag is implemented with the WISP programmable device based on the DL-WISP4.1 firmware. The WISP tag generally comprises two parts: the first part is the MSP430F2132 microcontroller which can work in ultra-low power, the second part is an antenna circuitry which can gather and backscatter signals. In the firmware of both USRP and WISP, most of operations (e.g., QUERY, ACK) specified in the EPCglobal Gen-2 standard have been implemented. After receiving the command, the aggregated responses from tags can be decoded at the reader.

One signal sample received at PHY layer can be represented as one complex symbol on the I-Q plan. But due to the dynamic environment (noises and interferences), the signal samples received with the same collision state are dispersed around a center point. Our symbol clustering algorithm aims at identifying the number of efficient clusters, based on the idea of defining cluster as connected dense components. As shown in Fig. 2(b)-2(d), the physical symbols in the I-Q plane exhibit distinct clustering patterns, depending on the number of colliding tags.

Our algorithm consists of two phases, which are the pre-processing phase, and the clustering phase. In the pre-processing phase, the reader captures the physical layer signals that tags concurrently transmit in a slot. Our algorithm divides the constellation plane into grids. Since areas of low-point density can be arbitrarily shaped in the data space, we roughly filter the noise of the physical layer symbols by making discretization for the physical layer symbols, as shown in Fig. 3(a). In the clustering phase, we cluster the signals to detect each slot state by DBSCAN, as shown in Fig. 3(b). Fig. 4 plots the state detection accuracy of the clustering algorithm. The x-axis of Fig. 4 is the ground truth of each tag response state, and the y-axis represents the detection results. In an actual environment, wireless communications is error-prone. Channel error may corrupt the data exchanged between the reader and tags. For example, if the preamble from a tag disturbed by the channel noise, the accuracy of our algorithm will decrease. We will evaluate the impact of the clustering accuracy on PUTI in Section VI.

V. Physical-Layer Unknown Tag Identification Protocol

A. *Basic Idea*

We propose the Physical-layer Unknown Tag Identification protocol (PUTI) to identify the entire unknown tags by utilizing the physical layer information. The idea follows three guidelines to achieve high time efficiency.

First, to efficiently avoid the recollection of known tags' IDs, PUTI can pick known tags out before the ID collection of unknown tags. This design of deactivating known tags prohibits their involvement in the identification of unknown tags.

Second, by plotting te collided signals from tags in a slot to I/Q plane, the reader can exact the number of concurrent tag responses. Taking the total number of tags replied in a slot can help the reader predict whether only known tags reply in current slot. Then the reader can easily pick them out from unknown tags without transmitting known tags' IDs.

Third, with N a priori, PUTI can mark most unwanted tags by using filtration technique before picking known tags. By this filtration technique, the reader can reduce the transmission overhead, which further improves the efficiency.

Therefore, PUTI is a cross layer protocol of RFID network stack, which improves the operational efficiency of RFID systems fundamentally.

PUTI consists of two phases which are the *filtration phase* and the *identification phase*. In the filtration phase, the reader exploits physical layer signals to separate tags. When the filtration phase ends, the entire known tags keep silence in the following phase. Then the reader adopts the well-known protocol to identify all the unknown tag IDs in the identification phase. By performing a joint optimization to minimize the combined overhead of two phases, the end result is a protocol that is far superior than the promising protocols.

B. Phase 1: Filtration

The filtration phase of PUTI follows the Reader-Talks-First principle (as shown in Fig. 5). When the RFID reader first powers and contacts the tag, clock and identification data is transmitted. In both Step 1 and Step 3, reader transmits a high power waveform query (bit vector) to operate the tags, which is similar to typical sequential identification methods. In Step 2, tags reply in a selected slot. If n tags reply at the same time in a slot, 2^n symbol clusters are formed in the corresponding constellation map. Therefore, the total number of different states shown in the I/Q plane indicates the number of tags selecting the current slot.

Marking unknown tags: As shown in Fig. 5, the reader constructs a vector $\mathbf{V}_A$ with f bits, by mapping all the known IDs to it. Specifically, an arbitrary known tag, the reader calculates the index i of replying slot where $i = H(ID, r)$ $mod\ f$. If none of the known RFID tags is mapped to this bit in $\mathbf{V}_A$, the reader set this bit to '1'. On the contrary, if one or more known tags select the bit, the reader set it to '0'. In Fig. 5, the known tags t_1, t_6, t_7 and t_9 select the second, forth, sixth bit respectfully, then the reader generates the vector "101010" based on the selection of these known tags.

After constructing the vector $\mathbf{V}_A$, the reader first broadcasts a request with parameter $\langle r, f\rangle$, where f is the length of the vector and r is a random seed. Note that the parameter $\langle r, f\rangle$ is used for mapping IDs to each bit by tags. The reader then broadcasts the indicating vector $\mathbf{V}_A$ to all the tags, including both known tags and unknown tags. If the vector is too long, the reader can split it into 96-bit segments and transmit each of them in a time slot of length t_{id}. Therefore, the location of '1' in the vector indicates that no known tags selects the bit. Therefore, if any tag finds its mapping bit is equal to '1', it means the tag is unknown to the server.

Upon receiving the reader requests, each tag selects a slot to reply. Since the tags have the knowledge of the vector index

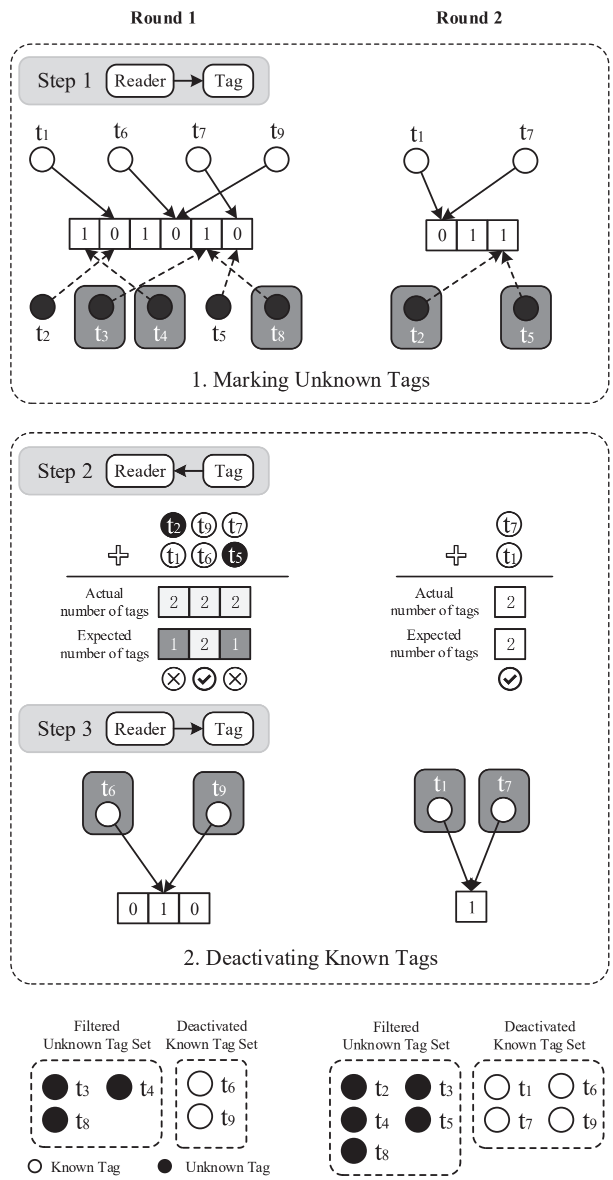


Fig. 5. Illustration of PUTI protocol.

they belong to, checking the corresponding bit of the indicating vector $\mathbf{V}_A$ from the reader makes the tag whether mark itself as unknown or not. If the i-th bit of $\mathbf{V}_A$ equals '0' (i.e., $\mathbf{V}_A[i] =' 0'$), the tag selects the i-th bit will participate in the following step. On the contrary, if the i-th bit of $\mathbf{V}_A$ equals '1' (i.e., $\mathbf{V}_A[i] =' 1'$), the tag from selects the i-th bit will mark itself as a unknown tag and keep silence until the filtration phase ends.

When the tag compares its bit index with the vector $\mathbf{V}_A$, it also counts the total number of '1' bits before the i-th bit in the indicating vector $\mathbf{V}_A$. Here we denote the total number of '1' bits as k_i, which indicates the slot index the tag will reply in. If a tag selects the i-th bit of $\mathbf{V}_A$ and $\mathbf{V}_A[i] =' 1'$, the tag will reply in the k_i-th slot.

Deactivating known tags: With N as a priori, the reader knows the expected number of tags in each slot, when there are no unknown tags. We denote the expected number of known tags in current slot as k. In the meantime, by plotting the actual collided signals from tags in a slot to I/Q plane, the reader can exact the number of concurrent tag responses in the slot. We denote the number of total tags in current slot as s. Then we can easily know, if unknown tags reply in the slot, s and k will be different, i.e., $s \neq k$. Therefore, the difference between the expected slot state and the actual one can be used to pick the known tags from unknown tags.

Note, when increasing the number of tags in a slot, the performance using this method degrades. Because the clusters in the I/Q plane will be closer to each other, when the number of clusters increase, which impacts the accuracy. We denote the threshold as ϕ. Then if the number of tags reply in a slot is larger than the threshold ϕ, we assume the reader is unable to exact the number of concurrent tag responses.

Within the threshold ϕ, the reader can predict whether only known tags reply in current slot. Then the reader can easily pick them out from unknown tags without transmitting known tags' IDs.

The reader set the vector $\mathbf{V}_B$. For an arbitrary slot i, we can set the bit $\mathbf{V}_B[i]$ as follows:

- If $s = k$, $\mathbf{V}_B[i] = 1$.
- If $s < k$, $\mathbf{V}_B[i] = 0$.

When $s = k$, it means only known tags reply in i-th slot. The reader sets the i-th bit of the vector as $\mathbf{V}_B[i] = 1$. When known tags check the corresponding bit of $\mathbf{V}_B$, they know they are known tags to the system, and they will not participate in the identification phase.

When $s < k$, it means both known tags and unknown tags reply in i-th slot. The reader sets the i-th bit of the vector as $\mathbf{V}_B[i] = 0$. When both known tags and unknown tags check the corresponding bit of $\mathbf{V}_B$, and they will continue to the next round.

The reader then broadcasts the vector $\mathbf{V}_B$ to both known tags and unknown tags. If the vector is too long, the reader can split it into 96-bit segments and transmit each of them in a time slot of length t_{id}. Until all the known tags are deactivated, the reader starts to identify the intact unknown tag set.

Example Case: To show how PUTI works in the filtration phase, we raise an example as illustrated in Fig. 5. The initial candidate tag set is $\{t_1, t_2, ..., t_9\}$, in which 9 tags are in the system. There are 4 known tags which are $N = \{t_1, t_6, t_7, t_9\}$, and 5 unknown tags which are $M = \{t_2, t_3, t_4, t_5, t_8\}$. Fig. 5 illustrates two rounds execution of PUTI. In the first round, the reader broadcasts the vector $\mathbf{V}_A = 101010$ to the tags in the system. Because tag t_3, t_4 and t_8 find '1' in the first and fifth bits, they mark themselves as unknown tags and keep silent until the filtration phase ends. The rest tags t_1, t_2, t_5, t_6, t_7 and t_9 reply the their bit strings to the reader. According to the aggregated signal bit string from tags, the second bit in the string is the exclusive bit, thus the reader set the vector $\mathbf{V}_B = 010$. Then the reader sends the vector $\mathbf{V}_B$ to the tags. Because tag t_6, and t_9 find '1' in the second bit of the vector $\mathbf{V}_B$, they are deactivated in the following phase. With the same filtration approach, the reader can filter all the unknown tags in the second round, as shown in the figure.

C. Phase 2: Identification

After all the knowntags are filtered, the filtration phase ends and the collection phase starts. Since our work focuses on filtering known tags from unknown tags, in the collection phase, we adopt the well-known ID collecting technique to collect the IDs of unknown tags. After the collection phase, the reader can access to the IDs of entire unknown tags.

D. Joint Optimization

In this subsection, we discuss how to set optimal frame size in PUTI to maximize the efficiency of filtering known tags in each round.

We define the efficiency of filtering known tags as θ, the total execution time as T and the total expected number of deactivated known tags as λ. Then we can have:

$$\theta = \frac{\lambda}{T}. \tag{6}$$

We first calculate the total expected number of deactivated known tags and then the total execution time.

Lemma 1. *Given f, the probability (denoted as Pr(A)) of the slot which no more than ϕ known tags select is*

$$Pr(A) = \sum_{k=1}^{\phi} \binom{n}{k} \left(\frac{1}{f}\right)^k \left(1 - \frac{1}{f}\right)^{n-k}. \tag{7}$$

Proof: We know the length of the vector is f, thus the probability for each known tag select a slot to reply is $\frac{1}{f}$. If the reader wants to pick up known tags through the current slot, there must be no more than ϕ. Let $\mathbb{N}$ represent the number of known tags select the slots to reply. When $\mathbb{N} = 1$, we have

$$Pr(\mathbb{N} = 1) = \binom{n}{1} \frac{1}{f} \left(1 - \frac{1}{f}\right)^{n-1}. \tag{8}$$

Therefore, the probability of the effective slot which can be used to construct the linear equations in a round is

$$\begin{aligned} Pr(A) &= \sum_{k=1}^{\phi} Pr(\mathbb{N} = k) \\ &= \sum_{k=1}^{\phi} \binom{n}{k} \left(\frac{1}{f}\right)^k \left(1 - \frac{1}{f}\right)^{n-k}. \end{aligned} \tag{9}$$

■

Lemma 2. *Given f, the probability (denoted as Pr(C)) of the slot which can deactivate the known tags is:*

$$Pr(C) = \sum_{k=1}^{\phi} \binom{n}{k} \left(\frac{1}{f}\right)^k \left(1 - \frac{1}{f}\right)^{n-k} \left(1 - \frac{1}{f}\right)^m \tag{10}$$

Proof: A bit which the reader can use to deactivate known tags is the slot none of unknown tags selects. The probability of a tag hashes into a bit is $1/f$. Therefore, the probability of an unknown tag does not hash in to the current slot is $1 - 1/f$. To deactivate the known tags successfully in a slot, none of the unknown tags should select it. The probability of no unknown tags select the slot (denoted as $Pr(B)$) is

$$Pr(B) = \left(1 - \frac{1}{f}\right)^m. \tag{11}$$

So the probability known tags can be deactivated is equal to

$$\begin{aligned} Pr(C) &= Pr(A)Pr(B) \\ &= \sum_{k=1}^{\phi} \binom{n}{k} \left(\frac{1}{f}\right)^k \left(1-\frac{1}{f}\right)^{n-k} \left(1-\frac{1}{f}\right)^m, \end{aligned} \quad (12)$$

■

Then the total expected number of deactivated known tags in a round is:

$$\begin{aligned} \lambda &= \sum_{k=1}^{\phi} k \times Pr(\mathbb{N}=k)Pr(B) + \sum_{k=\phi}^{n} 0 \times Pr(\mathbb{N}=k)Pr(B) \\ &= \sum_{k=1}^{\phi} k \binom{n}{k} \left(\frac{1}{f}\right)^k \left(1-\frac{1}{f}\right)^{n-k} \left(1-\frac{1}{f}\right)^m. \end{aligned} \quad (13)$$

Lemma 3. *Given f, the length of the slots and the vector in the second step of the filtration phase (denoted as l) is:*

$$l = f\left(1-\frac{1}{f}\right)^n \quad (14)$$

Proof: In the second step of the filtration phase, the length of the slots and the vector $\mathbf{V}_B$ are the same. Here we denoted the length as l. The location of '1' in the vector $\mathbf{V}_A$ indicates that no known tags selects the bit. Therefore, if any tag finds its mapping bit is equal to '1', it means the tag is unknown to the server. Then the tag marks itself as unknown tag, and keeps silence until the identification phase. We can deduce the probability of the bit can be used to filter the unknown tags as follows:

$$Pr(D) = \left(1-\frac{1}{f}\right)^n, \quad (15)$$

where D is the event unknown tags can be filtered and f is the frame size. Therefore, the expected length l should be

$$l = fPr(D) = f\left(1-\frac{1}{f}\right)^n. \quad (16)$$

■

Then we denote t_l as the time that a tag replies a slot. t_{ID} is denoted as the time a reader takes to send ID order. Therefore, the total execution time T is:

$$\begin{aligned} T &= \left\lceil \frac{f}{96} \right\rceil t_{ID} + t_{ID} + lt_l + \left\lceil \frac{l}{96} \right\rceil t_{ID} \\ &\approx \frac{f}{96} t_{ID} + lt_l + \frac{l}{96} t_{ID}. \end{aligned} \quad (17)$$

Substituting Eqn 13 and 17 into Eqn 6 can obtain the efficiency of filtering known tags (θ) as follows:

$$\theta = \frac{f\sum_{k=1}^{\phi} k\binom{n}{k}\left(\frac{1}{f}\right)^k \left(1-\frac{1}{f}\right)^{n-k} \left(1-\frac{1}{f}\right)^m}{\frac{f}{96}t_{ID} + lt_l + \frac{l}{96}t_{ID}}, \quad (18)$$

which is a function with respect to only f when n and m are foreknown. It is easy to get the optimal length f to find the maximal efficiency θ.

Fig. 6 illustrates the efficiency of the filtration with respect to the different frame sizes, where $n = 10,000$, $m = 10,000$ and $t_{ID} = 2.4ms$. We can clearly see that the efficiency of

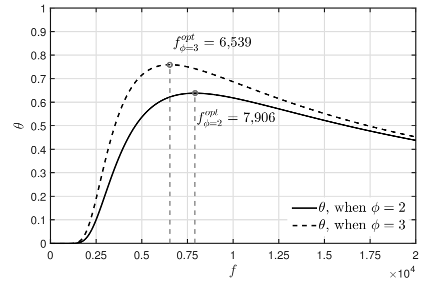


Fig. 6. The efficiency of the filtration with respect to the frame size f.

the filtration phase increases as the frame size f increases. When $\phi = 3$, after reaching the maximum when $f = 6,539$, the efficiency decreases with f.

E. Protocol Analysis

In this subsection, we will analysis the protocol in each round. For the sake of clarity, we take the subscription i on each variable to represent the round index. We first analysis the expected number of known tags left in each round, and then analysis the expected number of unknown tags left in each round.

As Eqn 13 mentioned, the number of deactivated known tags (denoted as n'_i) is λ. For the next round $i+1$, we can take recursive equation to represent the number of known tags remained as follows:

$$\begin{aligned} n_{i+1} &= n_i - n'_i = n_i - \lambda \\ &= n_i - f_i \sum_{k=1}^{\phi} k \binom{n_i}{k} \left(\frac{1}{f}\right)^k \left(1-\frac{1}{f_i}\right)^{n_i-k} \left(1-\frac{1}{f_i}\right)^{m_i}. \end{aligned} \quad (19)$$

We then analysis the expected number of unknown tags remained in each round.

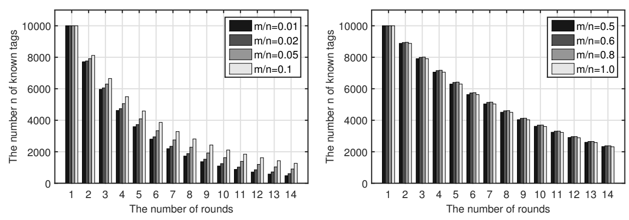
Lemma 4. *For an arbitrary round i, the expected number of the marked unknown tags is*

$$m'_i = m_i \left(1-\frac{1}{f_i}\right)^{n_i}. \quad (20)$$

Proof: We first consider the expected number of marked unknown tags through a slot, which is denoted as E[D]. According to the description above, the reader definitely marked the unknown tags only if there is no tag from the set of N_i and at least one tag from the set of M_i. We know the probability of that no tag is from the set of N_i is $Pr(D)$. We denote the probability of that j tags are from the set M_i as $Pr(\mathbb{M}_i = j)$. Due to the frame size f_i, selecting the current bit has a probability of $1/f_i$. The probability of j tags are from the set of M_i can be conducted as:

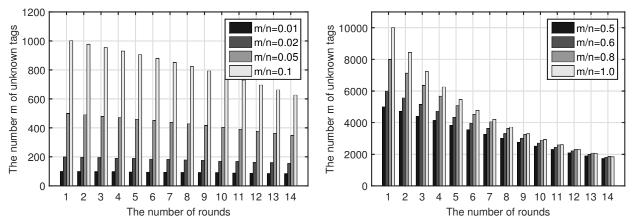
$$Pr(\mathbb{M}_i = j) = \binom{m_i}{j} \left(\frac{1}{f_i}\right)^j \left(1-\frac{1}{f_i}\right)^{m_i-j}. \quad (21)$$

Thus, combining $Pr(D)$ and $Pr(\mathbb{M}_i = j)$ gets the expected



(a) (b)

Fig. 7. The change of expected number of known tags in each round, where the initial number of known tags is set to $n = 10,000$: (a) m/n ratio is low. (b) m/n ratio is high.



(a) (b)

Fig. 8. The change of expected number of unknown tags in each round, where the initial number of known tags is set to $n = 10,000$: (a) m/n ratio is low. (b) m/n ratio is high.

number of identified relations $E[D]$ as:

$$\begin{aligned} E[A] &= \sum_{j=0}^{m_i} jPr(D)Pr(\mathbb{M}_i = j) = Pr(D)\sum_{j=0}^{m_i} jPr(\mathbb{M}_i = j) \\ &= Pr(D)\sum_{j=0}^{m_i} j\binom{m_i}{j}\left(\frac{1}{f_i}\right)^j\left(1-\frac{1}{f_i}\right)^{m_i-j} \\ &= Pr(D)\frac{m_i}{f_i} = \frac{m_i}{f_i}\left(1-\frac{1}{f_i}\right)^{n_i}. \end{aligned} \tag{22}$$

Because the length of the vector is equal to f_i, the expected number of the marked unknown tags is $m_i' = f_iE[D] = m_i(1-\frac{1}{f_i})^{n_i}$. ∎

Therefore, for the next round $i+1$, we can take recursive equation to represent the number of unknown tags remained as follows:

$$\begin{aligned} m_{i+1} &= m_i - m_i' \\ &= m_i - m_i\left(1-\frac{1}{f_i}\right)^{n_i} \\ &= m_i\left(1-\left(1-\frac{1}{f_i}\right)^{n_i}\right). \end{aligned} \tag{23}$$

Since the recursive equation has no analytical solution, the expected number of known tags n_i and m_i remained in each round cannot be deduced. We use Fig. 7 to illustrate the curve of the function. In the figure, the number of known tags $n = 10,000$. Fig. 7(a) shows that when m/n ratio is low (between 0.01 and 0.1), the expected frame size f_i declines sharply as the increase of the round. As the same trend with low m/n ratio, Fig. 7(b) also reveals that when m/n ratio is high (between 0.5 and 1), the expected frame size f_i declines sharply.

Then we use Fig. 8 to illustrate the change of frame size f_i in each round. In the figure, the number of known tags $n = 10,000$. Fig. 8(a) shows that when m/n ratio is low (between 0.01 and 0.1), the expected frame size f_i has a slight decline at the initial rounds. Because the density of known tags is high, the empty slots are almost occupied by known tags. More specifically, when $m = 500$, the frame size f_i has a significant decline after 8th round ends. Fig. 8(b) reveals that when m/n ratio is high (between 0.5 and 1), the expected frame size f_i declines sharply at the initial round.

F. Cardinality Estimation

As mentioned in previous subsection, to set the optimal frame size, the server needs to estimate the cardinality for the set of unmarked unknown tags (i.e., M_i). Many estimation schemes have been proposed [27], [28] to achieve fast and reliable estimation. But utilizing those separate estimation protocols will increase the execution time. We propose an estimation scheme without extra time consuming by using the information identified in each round.

Consider the previous round, there are n_i tags actually in the set of N_i. To set the optimal frame size in each round, the server should know the number of cardinality of both n_i and m_i. Although the server can precisely count the number of n_i, the number of m_i can hardly be known. So it must take the scheme as following to estimate the number of unknown tags remained in the system which is denoted as $\widehat{m_i}$.

Before the round i, the reader can calculate the exact number of slots which no more than ϕ known tags select (denoted as α_i). After the round i, the reader also can easily obtain the actual number of slots which is used to deactivate known tags (denoted as β_i). Due to the existence of the unknown tags, we know $\alpha_i \neq \beta_i$. Multiplying f_i with both sides of Eqn 12 gets as follows:

$$\begin{aligned} f_iPr(C) &= f_iPr(A)Pr(B) \\ &= (f_iPr(A))Pr(B). \end{aligned} \tag{24}$$

Here, $f_iPr(A)$ can be treated as the expected number of slots which no more than ϕ known tags select. $f_iPr(C)$ can be treated as the expected number of slots which is used to deactivate known tags. Therefore, we can have the following equation:

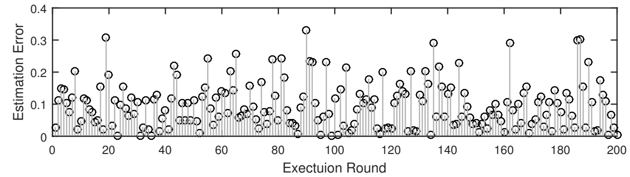
$$\begin{aligned} \beta_i &= \alpha_iPr(B) \\ &= \alpha_i\left(1-\frac{1}{f_i}\right)^{\widehat{m_i}} \\ &\approx \alpha_i\exp\left(-\frac{\widehat{m_i}}{f_i}\right). \end{aligned} \tag{25}$$

Therefore, we can deduce the $\hat{m}_i$ as:

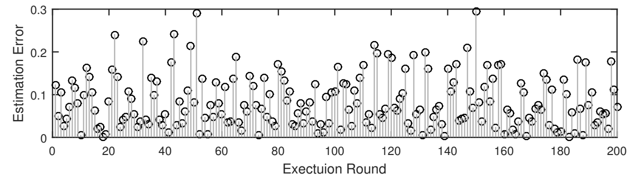
$$\widehat{m_i} = -f_i\ln\left(\frac{\beta_i}{\alpha_i}\right) \tag{26}$$

From Eqn 23, we know $m_{i+1} = m_i(1-(1-\frac{1}{f_i})^{n_i})$. From Eqn 14, we know $(1-\frac{1}{f_i})^{n_i} = l_i/f_i$. We denote l_i/f_i as γ_i. Then we can estimate the number of unknown tags in the next round by the following equation:

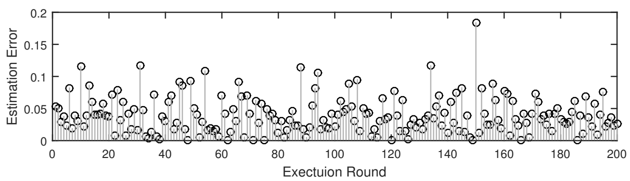
$$\widehat{m_{i+1}} = \widehat{m_i}(1-\gamma_i) = -f_i\ln\left(\frac{\beta_i}{\alpha_i}\right)(1-\gamma_i) \tag{27}$$



(a) Estimation error when $n = 10,000$, $m = 1,000$



(b) Estimation error when $n = 10,000$, $m = 5,000$



(c) Estimation error when $n = 10,000$, $m = 10,000$

Fig. 9. Estimation error when m changes. (a) $n = 10,000$, $m = 1,000$. (b) $n = 10,000$, $m = 5,000$. (c) $n = 10,000$, $m = 10,000$.

Fig. 9 plots the estimation error of our algorithm when m varies from $1,000$ to $10,000$, assuming $n = 10,000$. For each m, we plot the estimation error in 200 independent executions of PUTI. We can easily obtain that the estimation error decreases when m grows. In most cases, the estimation error is around 0.1. We will also evaluate the estimation error impact on our protocol in Section VI.

G. Discussion

As described above, PUTI consists of two phases: the filtration phase that isolates unknown tags from known tags and the identification phase that identifies separated unknown tags with the existing ID collection protocols. The second identification phase is C1G2 compliant but the first filtration phase is not. We assert that the existing C1G2-compliant tags can support our protocol PUTI via some software modification instead of any hardware enhancement.

There are two major differences between PUTI and C1G2 protocols. First, compared with C1G2, PUTI needs the tag to transmit only RN16 rather than RN16 together with tag ID for counting the number of tags. This change actually eases the burden on the tags as they do not need to transmit extra tag ID. Second, PUTI needs to broadcast two vectors to silence known tags and pick out unknown tags. This is not supported by the C1G2 standard. However, the C1G2-compliant tags have the ability to do so. That is because the C1G2-compliant tags are able to check each bit of RN16 sent from the reader and compute CRC16 to examine the correctness in the C1G2 standard. This ability is similar to what the tags in PUTI needs for checking each bit in the two vectors.

Although PUTI is not completely compliant with C1G2, it needs only some software modification instead of hardware improvement on existing commercial tags.

VI. Performance Evaluation

In this section, we evaluate the performance of PUTI in a simulation environment, and compare it with state-of-the-art protocols.

A. Simulation Setting

Our protocols are compared with the both state-of-the-art tag collection protocols and unknown tag identification protocols. For fair comparison, we adopt the timing scheme defined in the EPCglobal C1G2 UHF tags [29] as the unit of the execution time for all protocols. The length t_{ID} is set to $2.4ms$ for transmission of a tag ID (96 bits) from a reader to tags. In BUIP, the tags need to send RN16 response for helping the reader to distinguish empty, singleton, and collision slots. The length t_l is set to $0.8ms$. We then set the transmission length t_b of a bit from a tag to the reader to $0.04ms$. The above parameter settings are also adopted in [16], [15]. We fix the probability parameter of FUTI and CU as 99%. The results are conducted by running 100 times simulation and averaging.

B. Performance Comparison

1) Tag Identification with Collision Recovery: We first evaluate the performance in comparison with the following RFID concurrent transmission schemes:

EPC:EPC is the conventional scheme adopted in the EPC Gen-2 standard [29].

SIC:SIC [30] utilizes the difference in delay, the channel fading, and the frequency of individual tags to separate the collided signals. By using the technique of successive interference cancellation (SIC), tag IDs can be decoded from collisions.

Buzz:Buzz [31] identifies all tags and decodes tag collisions bit by bit assuming that the channel coefficients would linearly combine at the reader.

BiGroup: BiGroup [32] exploits the upper-layer communication patterns and leverages bipartite grouping to substantially improve the performance of physical layer collision recovery.

Our protocol PUTI consists of two phases: the filtration phase that isolates unknown tags from known tags and the identification phase that identify separated unknown tags with the existing ID collection protocols. The performance of the second phase relies on the efficiency of ID collection protocol that we use. If the ID-collection protocol is time-efficient, the second phase is efficient too. Otherwise, the second phase is time-consuming. Hence, the performance gains of this paper depend on the first phase and our objective is to design efficient protocol to achieve the first phase as soon as possible.

Therefore, four groups are generated, as shown in Table I and II. Here, we let $\theta = 3$. We will detail the θ in following subsection.

In Table I, we fix number of known tags $n = 10,000$ and vary number of unknown tags m from 500 to 1000. These

TABLE I
TOTAL EXECUTION TIME (S) EVALUATION OF TAG IDENTIFICATION WITH COLLISION RECOVERY PROTOCOLS. COMPARE PUTI WITH EPC, SIC, BUZZ AND BIGROUP IN DIFFERENT SIMULATION ENVIRONMENT. RATIO m/n IS FROM 0.05 TO 0.10.

Group		The number of unknown tags m					
		500	600	700	800	900	1,000
1	PUTI	7.76	8.51	9.22	9.88	10.61	11.31
	EPC	71.29	72.08	72.76	73.44	74.23	74.82
2	PUTI	7.11	7.65	8.34	8.89	9.49	10.06
	SIC	57.97	58.52	59.12	59.63	60.44	60.73
3	PUTI	5.46	5.69	5.92	6.14	6.40	6.67
	Buzz	22.21	22.42	22.66	22.84	23.32	23.26
4	PUTI	4.99	5.15	5.26	5.41	5.62	5.80
	BiGroup	12.93	13.04	13.16	13.64	13.72	13.88

TABLE II
TOTAL EXECUTION TIME (S) EVALUATION OF TAG IDENTIFICATION WITH COLLISION RECOVERY PROTOCOLS. COMPARE PUTI WITH EPC, SIC, BUZZ AND BIGROUP IN DIFFERENT SIMULATION ENVIRONMENT. RATIO m/n IS FROM 0.5 TO 1.0.

Group		The number of unknown tags m ($\times 10^3$)					
		5.0	6.0	7.0	8.0	9.0	10.0
1	PUTI	39.3	46.2	53.1	59.9	66.8	73.7
	EPC	102.2	108.5	115.1	122.8	129.8	136.9
2	PUTI	32.9	38.9	44.2	49.7	55.3	60.9
	SIC	82.2	88.8	93.4	99.1	104.2	110.2
3	PUTI	15.9	18.1	20.3	22.5	24.7	26.9
	Buzz	31.2	33.8	35.1	38.6	40.8	42.7
4	PUTI	11.7	12.4	14.7	15.4	16.7	18.5
	BiGroup	18.4	19.2	20.9	22.4	23.5	24.1

figures describe the low ratio m/n cases in which the number of unknown tags is far less than known tags. It is obvious that PUTI is much superior to the other four protocols. For an example of Group 1, when $m = 800$, PUTI consumes approximately $9.88s$ to complete the identification. In the meantime, EPC consumes about $73.44s$.

Table II shows that PUTI also has the improvement from relatively low ratio m/n to relatively high ratio m/n. In comparison, the number of known tags is fixed at $n = 10,000$ and the number of unknown tags m varies from $5,000$ to $10,000$. As shown in the figures, PUTI has a gradually rising in growth rate with increasing m. Although the performance gains are less than the case low ratio m/n, PUTI still outperforms the other four protocols. That is because with the increase of unknown tags, the identification time in the second phase increases, weaken the performance improvement caused by the first phase. For an instance of Group 3, when $m = 9,000$, PUTI consumes 24.7s to identify all the unknown tags. In the meantime, Buzz consumes about 40.8s to finish the identification.

2) Deterministic Unknown Tag Identification: We then compare PUTI with BUIP, BUIP-CE and BUIP-CF which can collect the entire unknown tag IDs. For complete comparison, the evaluation is run with a group of different parameters. Here, we let $\theta = 3$.

In Fig. 10(a), the simulations are conducted under the fixed number of known tags $n = 10,000$ and the various number of unknown tags $m \in [100, 600]$. Fig. 10(a) describes the low m/n ratio cases in which the number of unknown tags is far less than known tags. It is obvious that the time cost of unknown tag identification has a steady rise tendency as the number of unknown tags increases. However, PUTI uses less time than the other three protocols. More specifically, when $m = 500$, PUTI consumes approximately $7.76s$ to complete the identification. While BUIP, BUIP-CE and BUIP-CF cost about $26.29s$, $23.12s$ and $15.61s$ respectively. Due to utilizing the physical layer information, PUTI outperforms the other three protocols.

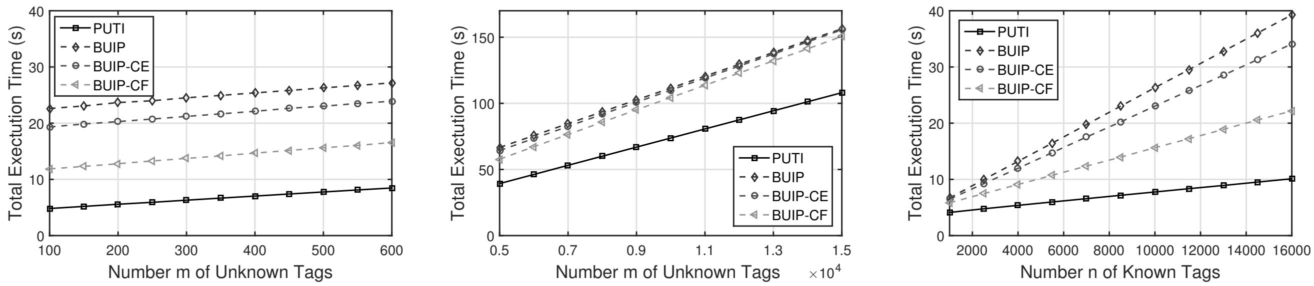
Fig. 10(b) shows that PUTI gets the improvement with the high m/n ratio. In the comparison, the number of known tags is fixed at $n = 10,000$ and the number of unknown tags m varies from $5,000$ to $15,000$. The curves of PUTI illustrates a gradually rising in growth rate with increasing m. As shown in the Fig. 10(b), PUTI costs less time compared with BUIP, BUIP-CE and BUIP-CF. For an instance, when $m = 9,000$, PUTI consumes 66.8s to identify all the unknown tags, while BUIP, BUIP-CE and BUIP-CF take $102.52s$, $100.82s$ and $95.12s$ respectively. In the high m/n ratio, the number of unknown tags is large. The identification phase costs much more time to identify unknown tags than the filtration phase.

Since the time of identification is affected by the number of unknown tags, we fix $m = 500$ and vary the number of known tags n from $1,000$ to $16,000$. Fig. 10(c) illustrates that PUTI has a fairly steady trend on total execution time when n changes. However, BUIP, BUIP-CE and BUIP-CF have a sharp increase on execution time. The reason for the efficiency improvement is that the optimal frame size of PUTI is mainly related to m, while optimal frame size of the BUIP, BUIP-CE and BUIP-CF is set $n + m$.

3) Probabilistic Unknown Tag Identification: We then compare our protocols PUTI with FUTI, CU which use the probability parameter to identify unknown tags at a level of accuracy. Note both CU and FUTI cannot collect all the IDs of unknown tags, we set the accuracy $\alpha = 99\%$. Because in the filtration phase, we make both PUTI and FUTI to use EPC standard identification scheme to identify the unknown tags. IFUTI modify the identification process of conventional scheme. For fair comparison, we only compare PUTI with FUTI. Here, we let $\theta = 3$.

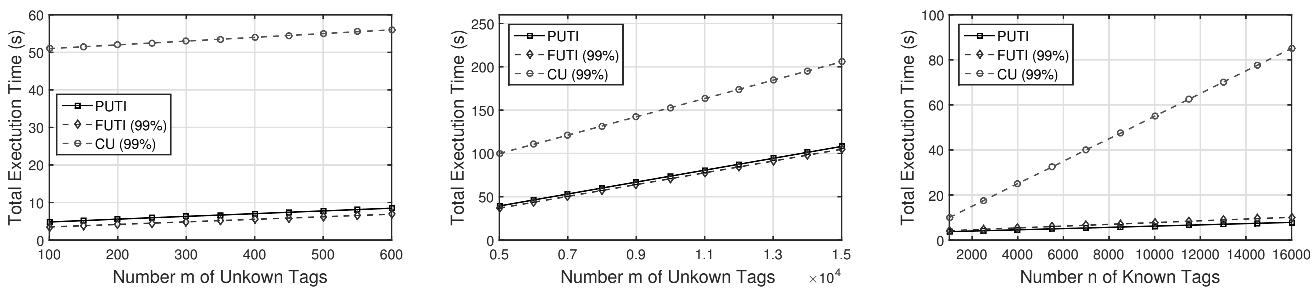
In Fig. 11(a), we set the number of known tags $n = 10,000$, and vary the number of unknown tags m from 100 to 600. As the Fig. 11(a) illustrates, PUTI and FUTI have a steady trend on consuming time when m grows. As m increases, PUTI and FUTI consume the less time in identifying unknown tags than CU. For an instance, when $m = 200$, PUTI consumes approximately $5.23s$, and FUTI consumes $4.91s$. In the meantime, CU consumes about 52.1s.

The Fig. 11(b) illustrates how the total execution time changes when m/n ratio gets higher. In the Fig. 11(b) shows the cases with fixed number of known tags $n = 10,000$ and the various number of unknown tags $m \in [5,000, 15,000]$. It can be seen that CU consumes much more time, both PUTI



(a) $n = 10,000$ with m/n ∈(0.01, 0.06) (b) $n = 10,000$ with m/n ∈(0.5, 1.5) (c) $m = 500$ with m/n ∈(0.02, 0.5)

Fig. 10. Total execution time evaluation of deterministic protocols. Compare PUTI with BUIP, BUIP-CE and BUIP-CF in different simulation environment.



(a) $n = 10,000$ with m/n ∈(0.01, 0.06) (b) $n = 10,000$ with m/n ∈(0.5, 1.5) (c) $m = 500$ with m/n ∈(0.02, 0.5)

Fig. 11. Total execution time evaluation of probabilistic protocols. Compare PUTI with FUTI, CU in different simulation environment.

and FUTI take less time than CU. For an instance, when $m = 6,000$, PUTI takes 46.24 to identify all the unknown tags. In the meantime, FUTI and CU take $43.86s$, $127.61s$ to identify the unknown tags with $\alpha = 99\%$ probability. In general, PUTI and FUTI have similar performance, which take less time than CU. However, as FUTI and IFUTI are probabilistic identification methods, they lose accuracy comparing with PUTI.

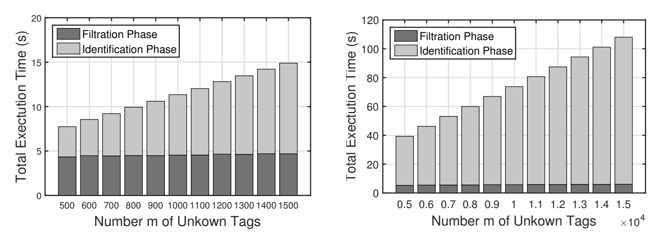
The same as in the comparison simulation performed in deterministic identification protocol, we fix $m = 500$ and vary the number of known tags n from $1,000$ to $19,000$. According to Fig. 11(c), the total execution time of PUTI and FUTI slightly grow when the number of known tags n raises. When m/n ratio grows, both PUTI and FUTI take less time than CU.

C. Protocol Investigation

The evaluation is executed with a group of different parameters. The first kind of simulations is conducted under the fixed number of known tags $n = 10,000$ and the various number of unknown tags $m \in [100, 600]$. It describes the low m/n ratio cases in which the number of unknown tags is far less than known tags.

The second kind of simulations is conducted under the fixed number of known tags $n = 10,000$ and the various number of unknown tags $m \in [5,000, 15,000]$. It describes the high m/n ratio cases in which the number of unknown tags is around the number of known tags.

For the sake of clarity, in the identification phase, we let the reader adopt EPC protocol to identify all the unknown tag IDs.



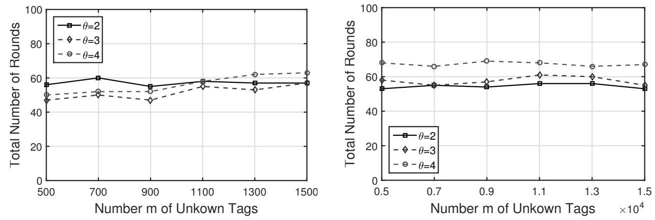
(a) (b)

Fig. 12. The efficiency investigation of the filtration phase (PUTI), where the initial number of known tags is set to $n = 10,000$: (a) m/n ratio is low. (b) m/n ratio is high.

1) Filtration Efficiency: We evaluate the efficiency of the filtration phase. As described in the paper, our protocol PUTI consists of two phases which are the filtration phase and the identification phase. In the filtration, the reader pick out known tags from unknown tags. Hence, only the unknown tags participate in the identification phase. Here, we let $\theta = 3$.

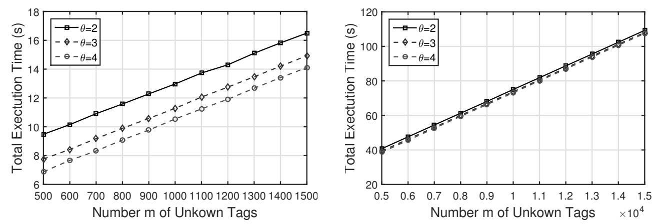
Fig. 12 shows the execution time of two phases in PUTI. When ratio m/n is low, both filtration phase and identification phase have impact on the unknown tag identification process. For example, when $m = 500$, the execution time of filtration phase is $4.32s$ and the execution time of collection phase is $3.41s$, which are 56% and 44% of the total execution time respectively. When ratio m/n is high, the filtration phase has little impact on the identification process. When $m = 14,000$, the filtration phase costs about $5.94s$ which is 5.8% of the total execution time.

Therefore, when an RFID system has a great number of unknown tags and a few known tags, the overhead to silence



(a) (b)

Fig. 13. Efficiency investigation of the total number of rounds (PUTI), where the initial number of known tags is set to $n = 10,000$: (a) m/n ratio is low. (b) m/n ratio is high.



(a) (b)

Fig. 14. The efficiency investigation of the impact of θ (PUTI), where the initial number of known tags is set to $n = 10,000$: (a) m/n ratio is low. (b) m/n ratio is high.

known tags can be neglected.

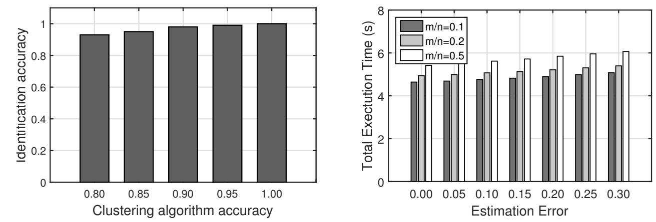
2) Total Number of Rounds: Fig. 13 plots the total number of execution rounds which the reader needs to finish unknown tag identification, when we fix $n = 10,000$ and vary m/n ratio. From the figure, we observe in the most cases of lower m/n ratio, PUTI finishes in searching in no more than 60 rounds. When the ratio of m/n grows, the more rounds PUTI needs to finish identification. For example, if $m = 9,000$, on average, the reader can identify the unknown tags in 70 rounds.

3) Impact of θ: We evaluate the impact of θ on the total execution time as shown in Fig. 14. When m/n ratio is low, both filtration phase and identification phase have impact on the unknown tag identification process. We can observe, when θ grows, the total execution time will decrease. When m/n ratio is high, the filtration phase has little impact on the identification process. The total execution time with the different value of θ is close.

D. Error Impact

1) Impact of Clustering Error: We then evaluate the impact of clustering algorithm accuracy on the total identification process. If clustering algorithm gets wrong slot type, the unknown tag identification result will suffer from bias. Fig. 15(a) plots the accuracy of unknown tag identification when the error of clustering algorithm exists, where we set $m = 1,000$, $n = 10,000$, and varying the clustering algorithm accuracy from 80% to 100%.

2) Impact of Estimation Error: To achieve the high efficiency in unknown tag identification, the server must set the optimal frame size by utilizing the number of known tags and unknown tags, i.e., n and m. In PUTI, we uses the cardinality



(a) (b)

Fig. 15. The efficiency investigation of error impact (PUTI). (a) Impact of clustering error. (b) Impact of estimation error.

estimation scheme to estimate the cardinality of unknown tags. However, the estimated $\hat{m}$ may deviate from the actual value. We investigate the impact of estimation error on the total execution time in PUTI, when m/n ratio varies from 0.1 to 0.5, assuming $n = 10,000$.

In Fig. 15(b), it can be seen that the execution time of the filtration phase increases slightly along with the increased estimation error. Obviously, when no estimation error exists, the execution time is the shortest. When the estimation error grows larger, the execution time only has a small increase. For an instance, when the estimation error is 0.25 and $m/n = 0.2$, comparing with no estimation error scenario, the execution time only has 2.2% increase. Thus, the estimation error is tolerable for PUTI.

VII. Conclusion

This paper investigates the problem of unknown tag identification in large-scale RFID systems. We propose a Physical-layer Unknown Tag Identification (PUTI) protocol that identifies all unknown tags efficiently by aggregating physical layer signals. Unlike prior work, the noticeable advantage of PUTI is that it takes full use of not only empty slots, but also singleton slots and collision slots. Moreover, we theoretically analyze the execution efficiency of PUTI. We implement a prototype system and validate our clustering algorithm design based on the Universal Software Radio Peripheral (USRP) platform and the Intel Wireless Identification and Sensing Platform (WISP). Simulation results show that our protocol outperforms prior unknown tag identification protocols, including both deterministic and probabilistic identification.

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