Unknown Tag Identification Protocol Based on Collision Slot Resolution in Large-Scale and Battery-less RFID System

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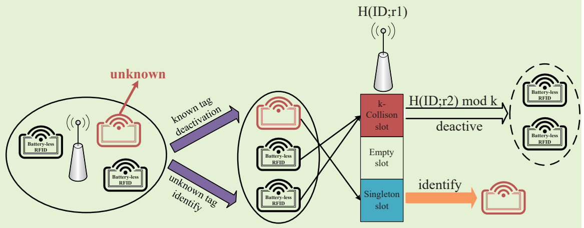
***Abstract*—Radio frequency identification (RFID) technology is widely used in warehouse management and supply chain management. In the actual application, unknown tags such as newly added or incorrectly placed products will be placed into a certain area of the warehouse. Existing identification protocols can identify such unknown tags by collecting tag IDs and comparing them with back-end server. Alternatively, the known tags can be filtered through the filter vector to prevent interference from unknown tags and improve identification efficiency. However, there is a lack of consideration of the collision impact on identification efficiency. In this paper, we introduce the bit tracking technology to accelerate the identification process and propose a Bit-Tracking Based Strategy for Unknown Tag Identification (BTUTI) protocol. We solve the problem by means of known tag deactivation and unknown tag identify. First, by adopting bit tracking technology, the reader can easily locate the positions of the collision bit. By hashing the tags of these collision slots, the collision slots can be turned into resolvable slots, thus improving the utilization rate of slots. Second, in the expected non-empty slot, the reader can send command to deactivate the known tag and skip empty slots and irresolvable collision slots. The experiment proves that BTUTI can increase the time efficiency compared to the state-of-the-art.**



***Index Terms*—battery-less RFID, unknown tags, time efficiency.**

I. Introduction

THE rapid development and applications of Radio Frequency Identification (RFID) technology [1], [2] have brought new opportunities for the Internet of Things (IoT) [3], [4]. In the wide range of applications of the Internet of Things, autonomous vehicles have gradually matured. Currently, photonic radar can be used to detect the location of targets at long distances [5], [6]. In addition, optical biosensors are gradually used in medical diagnosis and other aspects [7], [8]. And the communication between nodes in the RFID system uses a low-cost communication method to make the communication between nodes more efficient. In recent years, RFID technology has been rapidly promoted and applied in many fields, such as target tracking [9]–[11], inventory control [12]–[14], logistics management in the supply chain [15]–[17], etc. In warehouse management, RFID technology can be combined with goods storage and retrieval operations to automatically count goods. The use of bit-tracking technology can intelligently automate the work process, so that warehouse managers can retrieve product information and manage products more efficiently.

The sensing layer in the IoT architecture usually includes various sensors [18]–[22], and also brings some challenges. Existing sensors include sensors with batteries and sensors without batteries. A sensor with a battery [18], [19] is simply an electronic device, and the common denominator of all electronic devices is that they require power to operate. However, environmental sensors are deployed far and wide, often in remote, large spaces, such as factories and buildings. Therefore the use of a wired power supply is inefficient, and battery replacement is often very inconvenient. In fact, the same problem exists for sensors embedded in close but hard-to-reach places, such as the center of a machine. In contrast, battery-free wireless sensors can overcome these problems [20]–[22]. The main role of battery-free wireless sensor tags

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is in certain inaccessible or hard-to-reach places, such as underground, inside walls, inside containers, and in toxic or health-hazardous areas. It implements sensing on a single chip, harvesting energy from the received electromagnetic field signal, thus eliminating the need for batteries, and can monitor various parameters such as temperature, humidity, and distance, breaking through the limitations of traditional sensors.

In the RFID system, the tag that is misplaced outside its identification range is unknown. There are usually multiple tags within the query range of the reader, which will change the original singleton slot into a collision slot, thus causing many collision slots. This reduces the communication efficiency between the reader and the tag, thus reducing slot utilization and time efficiency. Although many works have been devoted to finding the unknown tags [23]–[25]. Most existing unknown tag identification protocols are with low time-efficiency for two reasons. First, the existing methods do not take into account the impact of collision slots on identification efficiency, thus wasting the utilization of information in collision slots. Second, the existing methods collect the IDs of tags in singleton slots for comparison with the back-end server, which will generate many collision and empty slots, resulting in prolonged execution time. Therefore, the existing works are hard to meet the needs of warehouse management.

In order to manage the warehouse efficiently, we propose a new solution called the Bit-Tracking Strategy Based for Unknown Tag Identification (BTUTI). BTUTI consists of the main filter vector construction stage, collision slot coordination stage, and tag verification stage. First, by using the results of tag mapping, we can filter out known tags in the singleton slot. Avoid repeating replies in the next round. Second, the tags in the collision slot are mapped to the additional vector by hash calculation. If they are all mapped into the singleton slot, it indicates that the collision slot can be resolved. The major contributions of this paper can be summarized as follows:

1) By effectively utilizing the tags in the collision slot, the waste of information in the collision slot is reduced. In addition, by hashing the tags of these collision slots again, the collision slots can be turned into resolvable slots, thus improving the utilization rate of slots.

2) The existing solution is to skip the idle slot directly during the tag verification phase. The BTUTI can directly skip the idle and uncoordinated slots in the verification phase, which speeds up the tag identification process.

3) We conduct rigorous theoretical analysis and simulation experiments to evaluate BTUTI. The numerical results show that our proposed BTUTI improves total execution time by 34.5% and the time efficiency by 28.9% compared to the best existing unknown tag identification method.

The remaining sections in this paper are organized as follows. Section II describes the related work. Section III gives the system model, problem description, and bit tracking technology. Section IV details the identification process of BTUTI and concludes this subsection with a theoretical analysis of the proposed method. Section V conducts the experimental simulation of BTUTI. Finally, Section VI concludes this paper.

II. RELATED WORK

In RFID-enabled applications, the existence of unknown tags poses a huge threat to financial loss and security. In recent years, how to find these unknown tags in a time-saving way has attracted widespread attention. Generally speaking, the methods for identifying unknown tags can be divided into two categories: 1) The first category is the unknown tag probability identification protocol. In short, these protocols can identify a certain probability of unknown tags, but they cannot guarantee that all unknown tags will be fully identified. 2) The second category is the complete unknown tag identification protocol, which can completely identify all unknown tags. In the following subsections, we will introduce some existing research work in detail.

A. Unknown Tag Probability Identification Protocol

First, Sheng et al [26] proposed the CU protocol, in which the reader first obtains a known tag ID by accessing the database. According to the expected and actual response results of the tag, the identity of the unknown tag can be judged. However, CU is a probabilistic identification protocol and cannot identify all unknown tags. Yang et al proposed a probabilistic approach called SEBA [27] protocol, which reduces the communication costs through batch verification of RFID tags. In SEBA, when the reader receives an unexpected response, it can be considered that there is an unknown tag. Bianchi et al [28] proposed the SEBA+ protocol, which sets up Bloom filters for multi-tag responses. It can be more easily used in scenarios with high detection capability requirements than SBEA. To improve the standard Bloom filter, Liu et al [29] proposed the SBF-UDP protocol, which takes into account the energy consumption problem when active tags are applied in unknown tag identification scenarios. In SBF-UDP, a method based on sampling is set up by improving the standard Bloom filter in SBEA+ protocol. Then the sampling bloom filter is sent to the tag, and the tag checks its corresponding bit in the sampling bloom filter according to the same parameters to determine whether it is an unknown tag. Although SBF-UDP protocol has better performance than the protocol that uses standard Bloom filter detection, it still has the characteristics of false positives, and unknown tag events cannot be detected deterministically.

In summary, these protocols are only used to detect whether unknown tags exist in the field. However, our purpose is not only to determine whether there is an unknown tags, it is important to confirm unknown tags.

B. Complete Unknown Tag Identification Protocol

Liu et al. [30] proposed the BUIP protocol, which uses three commands to distinguish the status of tags and prevents interference with the identification of unknown tags by keeping known tags silent. BUIP protocol realizes the complete identification of unknown tags for the first time. However, there are still many possibilities for improving the efficiency of the protocol. To achieve higher time efficiency, Liu et al. [31] further proposed the FUTI protocol, which maps known tags and unknown tags by setting filter vectors. FUTI protocol repeats multiple rounds until it reaches the expected percentage of identifying unknown tags. Qian et al. [32] proposed the TIP protocol, which takes into account the time-consuming of some methods in the identification stage. TIP method uses the indicator vector to let unknown tags send the ID only once in the identification process. Liu et al. [33] proposed a series of protocols. By allowing tags to select appropriate random numbers to avoid expected collisions, the known tags can be disabled quickly and the implementation efficiency of the protocol can be improved. However, some collisions can be avoided in this way, but additional transmission costs will be incurred, and the wasted collision slot information cannot be effectively utilized. Zhu et al. [34] proposed the PUTI protocol, which utilizes physical layer aggregation signals to separate unknown tags. Compared with the broadcast indicator vector method, PUTI protocol reduces the transmission time by effectively utilizing the mapping result of the tag. To further improve the performance of BUIP, Fu et al. [35] proposed the efficient LUTI protocol, which stores the results of tags mapping by setting two different indication vectors. The unknown tags are determined by the responses of the actual tags in the two different indication vectors. Then, considering the occasions where the unknown tags are relatively dense, the author proposed the HUTI protocol. HUTI scheme uses one indication vector to verify unknown tags and can perform better in the occasions where the unknown ratio is high. Chu et al. [36] proposed the EUTI protocol, which filters a known tag from multiple tags through the filter vector. In addition, EUTI protocol uses a reservation mechanism to reduce the transmission cost of idle slots.

In short, the existing unknown tag identification methods improve the overall identification time by reducing the interference of known tags to unknown tag identification. For example, three commands are used to distinguish the tag state method [30], set the filter method [31], [36], and set the indicator vector method [35] to avoid the interference of known tags as much as possible. The limitations of unknown tag identification protocols are mainly in time efficiency and the utilization rate of slot. The existing protocols do not take into account the impact of the utilization rate of slot on the time efficiency of identification. Considering that tags mapped to collision slots are not available for judgment, this will lead to the waste of collision information and more transmission overhead. Through the method of bit tracking, we know the number of tag responses in a slot and the result of mapping to determine those collision slots that can be solved. And further improve the utilization rate of slot, thus shortening the overall execution time and greatly improving the utilization rate of slot.

III. SYSTEM MODEL AND PROBLEM DESCRIPTION

A. System Model

Consider an actual RFID system as shown in Fig. 1, there are many battery-free RFID known and unknown tags in the warehouse. These tags are all within the communication range of the reader, which connects the identification result with the back-end server through Ethernet. The database stores the IDs of known tags. In large-scale RFID warehouse management systems, there are tens of thousands of known and unknown tags. In general, the proportion of these misplaced unknown tags is relatively small, but a high proportion of unknown tags (compared to the number of known tags) cannot be excluded. To validate the idea of large-scale, we set up experiments with small and large proportions of unknown tags and give the performance of the BTUTI compared to other methods in Section V.

Passive RFID tags with different sensing capabilities offer many viable solutions for the Industrial Internet due to the increasing popularity of battery-less RFID sensors. Due to its passive nature, no external battery power is required and printed circuits are usually used for mass production, so it is inexpensive and suitable for large-scale deployment and application. Generally speaking, the battery-less RFID sensor is a passive RFID tag, which is composed of the antenna and chip. Since its antenna impedance changes with various physical characteristics, it can be used to sense and identify relevant physical quantities such as temperature, sensing, humidity, pressure, etc. [37]–[39]. It provides more solutions for the Internet of Things to realize the interconnection between things. Battery-less RFID has many advantages of small size, easy deployment, long life, and maintenance-free in large-scale warehouse management, so this study also adopts battery-less RFID.

The peer mode of the RFID system is RTF (Reader Talk First) mode: the reader first sends the query command to the tag within the identification range, and then the tag sends the data to the reader. In RTF mode, the communication process between reader and tag is generally divided into three steps: the first step is to wake up the tag. The reader sends electromagnetic waves from the antenna and provides energy for the tag after coupling with the tag antenna. The tag is in a waiting state after being awakened. The second step is to send instructions. The reader sends the request data instruction to the tag. The third step is data transmission. The tag sends data to the reader. Finally, after the reader receives the tag signal, it modulates and demodulates the signal and sends it to the server for data processing. Taking the ALOHA algorithm as an example, the time axis is divided into time slots, and each tag randomly selects a slot for data transmission. According to the number of tag replies in the slot, these slots are divided into singleton slots (with one tag reply in the slot), idle slots (with no tag reply in the slot), and collision slots (with two or more tag replies in the slot). Due to the randomness of slots selected by tags, collisions are inevitable, and the number of three types of tags is also random. When the reader detects a collision, it can only resend slot parameters to start a new time slot, and the collision slot is wasted.

B. Motivation and Problem Statement

We consider that there are known tag sets and unknown tag sets in actual warehouse management, and the reader can only identify these known tags. Some products that are not

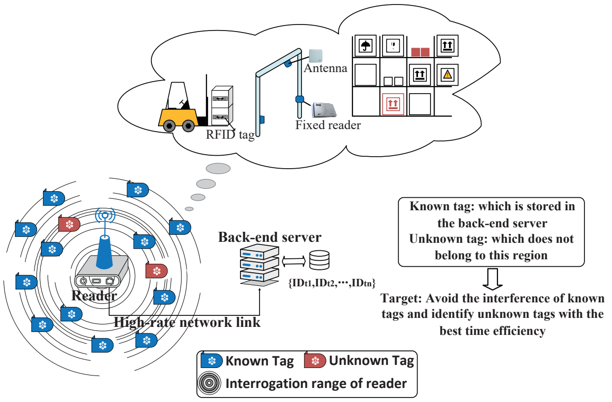


Fig. 1. System model.

TABLE I
NOTATIONS USED IN THIS PAPER

Symbols	Descriptions
N	The number of known tags
U	The number of unknown tags
S_k	The set of known tags
S_{uk}	The set of unknown tags
t_{tag}	The tag of slot
t_s	The short-response slot
F	Filter vector
f	The length of the filter
r	The random seed that is fresh in each round
$H(\cdot)$	The hash function with a uniform random distribution
θ	The average time for verifying the presence of one tag
α	the load factor is given by N/f

stored or put in the wrong area are called unknown tags. The known tag set is denoted as $\mathrm{S}_k, i.e.,\mathrm{S}_k = \{t1, t2, ...ti, ..., tN\}$; and the unknown tag set is denoted as $\mathrm{S}_{uk}, i.e.,\mathrm{S}_{uk} = \{tu1, tu2, ...tui, ..., tuU\}$. Since the IDs of known tags are stored in the database, it can know the tag's response information in advance. Table 1 summarizes the notations that are used in this paper.

In an RFID system, the loss caused by these misplaced unknown commodities cannot be ignored, so how to identify these unknown tags in an efficiently way is the problem that needs to be solved. The influence of different factors on execution time and execution efficiency are the indicators concerned in this paper.

C. Bit Tracking Technology

In the RFID system, if multiple tags transmit different bits at the same time, the rising and falling edges will be offset. However, the Manchester code does not allow this to happen during data transmission, so that the position of the collision bit can be judged. For existing unknown tags identification protocols, the interval time for each tag to reply with 1-bit information in a singleton slot consumes a lot of execution time. Therefore, based on the bit tracking technology, we consider enabling multiple tags to transmit information of a specified bit length in the same slot. Suppose there are three tags tag1, tag2, tag3 and the bit length is 6. Each tag selects a specific bit to transmit 1 and other bits transmit 0. Thus each collision bit can only represent the presence of one tag. As shown in Fig. 2, tags 1, 2 and 3 transmit signals encoded as "100000", "000100" and "000010", respectively. When these three tags respond to the reader in the same slot with Manchester encoding, offset will occur due to different signals. Therefore, the mixed signal received at the reader is "X00XX0", which indicates that there are three tags in the identification range.

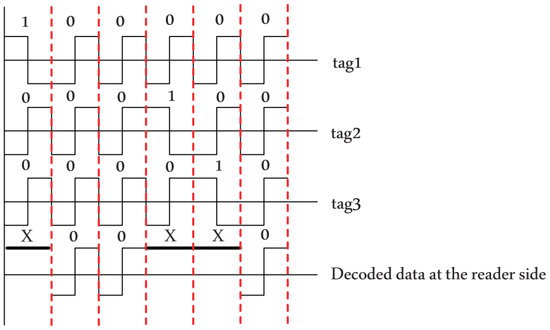


Fig. 2. An illustrated example of bit tracking technology.

IV. DESIGN OF THE BTUTI PROTOCOL

To manage the warehouse efficiently, we propose a new solution called Bit-Tracking Based Strategy for Unknown Tag Identification (BTUTI). Our proposed BTUTI protocol consists of three parts: 1) Construct the main filter vector. In this stage, the reader knows the time slot selected by the tag through pre-calculation. Then the main filter vector can be constructed based on the mapping results of all tags. 2) Collision slot coordination stage. After the first phase is complete, the reader can know which are the collision slots. By performing a second mapping of the tags in these collision slots, we can infer whether the collision slots can be coordinated from the mapping results of these collision tags. 3) Tag verification stage. By updating the main filter vector, the result of the tag mapping is judged and the reply of the tag is verified. The protocol runs round by round until all the tags have been identified.

In Algorithm 1, we give the pseudocode of the identification process of BTUTI. We assume an arbitrary time slot i, where N_s denotes the time slot counter, E denotes the number of empty slots, S denotes the number of singleton slots, and C denotes the number of collision slots. ID_{t_i} denotes the ID of any tag t_i, and ID_{t_ci} denotes the tag ID mapped to the collision slot. Step 1 initializes the relevant parameters. In steps 3$\sim$11, we map the tags once by the random number $r1$ and count the number of collision slots, singleton slots, and empty slots. For the tags in the collision slot, steps 12$\sim$23 in Algorithm 1 random number $r2$ is mapped twice to determine whether it can be coordinated. During steps 24$\sim$30, we identify the tag based on its actual response. This algorithm loops until all tags are identified. In the following subsections, we will elaborate on the three parts of BTUTI. Finally, we analyze the relevant parameters and optimize them to find the best execution time.

Algorithm 1 The identification process of BTUTI

```
Input: The number N of known tags; the number U of unknown tags.
Output: The number of total slots
$N_s \leftarrow 0$;$i \leftarrow 0$;$j1 \leftarrow 0$
while $N \neq 0$ and $U \neq 0$
    The reader broadcasts commands to tags
    $F[i] \leftarrow H(ID_{t_i}; r1)\ mod\ f$
    if The tag is mapped to this slot then
        $N_s \leftarrow N_s + 1$
    end if
    if $N_s > 1$ then $C \leftarrow C + 1$;$k \leftarrow N_s$
    else if $N_s == 1$ then $S \leftarrow S + 1$
    else $E \leftarrow E + 1$
    end if
    if This slot is the collision slot then
        $A[j1] \leftarrow H(ID_{t\_ci}; r2)\ mod\ k$
    end if
    for $j2 = 1 \rightarrow k - 1$
        if $A[0] \neq A[j1]$
            break
        end if
    end for
    if $j == k$ then
        This slot is a coordinating collision slot
        Update the value of $F[i]$
    end if
    if Expected response of tag in this slot==actual response then
        Identify as known tag
        $N \leftarrow N - 1$
    else
        Identify as unknown tag
        $U \leftarrow U - 1$
    end if
    $N_s \leftarrow 0$;$i \leftarrow 0$;$j1 \leftarrow 0$
end while
```

A. Construct the Main Filter Vector

Battery-less tags are activated by passive radio frequency. When the battery-less RFID tag is close to the RFID reader, the antenna of the battery-less RFID tag converts the received electromagnetic wave energy into electrical energy, activates the chip in the RFID tag, and sends out the data in the RFID chip. The reader receives the tag's ID and knows which slot in the filter vector is selected by the hash calculation. Before each round of tag mapping begins, the reader sends a query command to broadcast frame length f and random seed $r1$ to all tags within the identification range. After receiving the query command, the tag will respond to the reader. The reader uses these IDs to calculate $H(ID_{ti}; r1)$ mod f according to its tag ID and random seed $r1$. The state of each slot is represented by the main filter vector F. In the vector F, for any slot i, the calculation results of the tags can be divided into three categories: "0" represents an empty slot, "1" represents a singleton slot, and "k" represents a collision slot. Fig. 3(a) describes the construction process of the main filter vector, in which the dashed arrows represent the mapping results of known tags, and the solid arrows represent the actual mapping results containing unknown tags.

B. Collision Slot Coordination Stage

In this stage, the reader maps these tags in the collision slot again through another random seed $r2$. After the first stage, the reader can know which are the collision slots. Then we set additional vectors A to store the mapping results of tags in the collision slots. Suppose that there are k tags in any collision slot and let these k tags be mapped accordingly to an additional vector of length k. We can know the mapping result of these collision tags by calculating $H(ID_{t\_ci}; r2)$ mod k. Tags in collision slot are mapped from 0 to $k-1$ by random $r2$. When all tags in the collision slot are mapped to the singleton slot, it indicates that this collision slot can be resolved. Otherwise, the collision slot is unresolvable.

The coordination process of the collision slot is shown in Fig. 3(b). Based on the actual mapping results of the first stage, we can know that known tags $t1$, $t3$, $t5$, and unknown tag $tu3$ are all mapped to the second slot. Therefore, the length of the additional vector is set to 4. By calculating $H(ID_{t\_ci}; r2)$ mod 4, we obtain that the mapping results for these four tags are unique and have the same value. Therefore, the collision slot is resolvable. We code the resolvable and unresolvable collision slots with "10" and "01", respectively.

C. Tag Verification Stage

As shown in Fig. 3(c), the reader updates the main filter vector F by combining the main filter vector F and the additional vector A during the tag verification phase. The reader broadcasts a query command with parameters including $r1$, $r2$, f, and filter vector F. For the i-th slot of F, the value is set following the rules below:

1) If $F(i)$="0", which means that this slot is empty. In the next round of identification, these unmapped empty slots will be skipped directly.

2) If $F(i)$="1", which means that this slot is a singleton slot. The tag will remain silent during the next round of recognition and will no longer respond to the next recognition process.

3) If $F(i)$="01", which means that this slot is an irresolvable collision slot, the tag will not change its state in the next identification process, and continue to respond to the next round.

4) If $F(i)$="10", which means that this slot is a resolvable collision slot, the tag will remain silent during the next round of identification and will no longer respond to the next identification process.

On the reader side, it compares the received responses with F. Specifically, it checks each singleton slot and the strings in each resolvable collision slot. If the reader detects a difference, the corresponding tags are identified as unknown.

We use a practical example to illustrate the process of BTUTI. There are 6 known tags $S_k = \{t1, t2, t3, t4, t5, t6\}$ and four unknown tags $S_{uk} = \{tu1, tu2, tu3, tu4\}$ in the area, as shown in Fig. 3. The tags use the hash function $H(ID_{ti}; r1)$

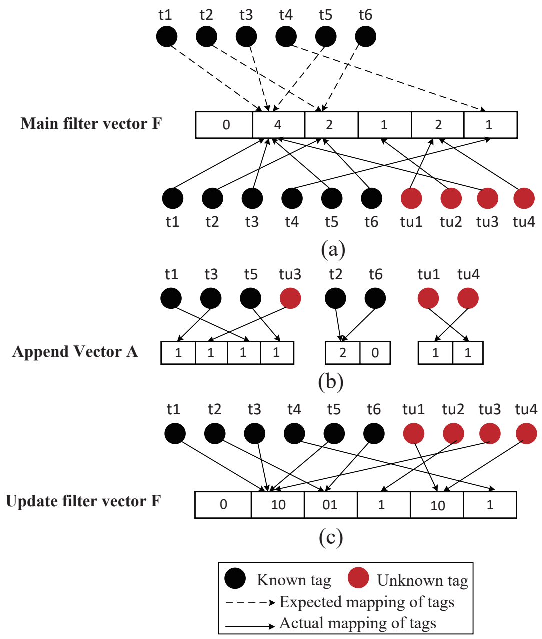


Fig. 3. An identification example of BTUTI: (a) Construct the main filter Vector, (b) Collision slot coordination Stage, (c) Tag verification stage.

mod f to construct the main filter vector F='042121'. For each k-collision slot, the reader sets the k-bit string and uses the hash function and random seed $r2$ to perform $H(ID_{t\_ci}; r2)$ mod k to map the tag in the collision slot. For example, $t1$, $t3$, $t5$, and $tu3$ mapped to the second slot are mapped to the 3rd, 1st, 4th, and 2nd bits of the 4-bit string, respectively. Therefore, the mapping result of the additional vector is '1111', which is the only and the same value. It means that this slot is coordinated, so the value in the vector is updated to F='010011101'. According to the rules, we can make the following judgment: For the second slot, from $F(2)$= "10", we can infer that this slot is a resolvable collision slot, so unknown tag $tu3$ is determined according to the actual response. For the third slot, from $F(3)$= "01", we can infer that this slot is an irresolvable collision slot, so the tags in this slot remain active and enter the next round of identification. For the fifth slot, from $F(5)$= "10", we can infer that this slot is expected to be empty, but in fact there are responses from two tags, so we can infer that these two tags are unknown. For the sixth slot, from $F(6)$= "1", we can infer that this slot is a singleton slot, so known tag $t4$ is determined according to the actual response.

D. Parameter Optimization

In this section, by analyzing the results of tags mapping, we can obtain the execution time of the BTUTI protocol. The execution time of BTUTI consists of three parts: 1) the time required to construct the filter vector and deactivate known tags; 2) The time to broadcast additional vectors; 3) The time required to verify unknown tags. By minimizing the execution time, we can obtain the optimal frame length required for each round of the identification process.

Assuming that the frame length is f, the probability that the tag chooses any bit in the vector is $1/f$. For any slot, the probability that k tags will choose to map to the same slot is

$$P_k = \binom{N}{k}\left(\frac{1}{f}\right)^k\left(1-\frac{1}{f}\right)^{N-k} \tag{1}$$

Let P_1, P_c denote the probability that there is an expected singleton slot and an expected collision slot among all considered slots, respectively. They are given as follows

$$P_1 = \binom{N}{1}\times\frac{1}{f}\times\left(1-\frac{1}{f}\right)^{N-1} = \frac{N}{f}\times e^{-\frac{N}{f}}\times e^{\frac{1}{f}} \approx \frac{N}{f}\times e^{-\frac{N}{f}} \tag{2}$$

$$P_c = \sum_{k=2}^{N} P_k = \sum_{k=2}^{N}\binom{N}{k}\times\left(\frac{1}{f}\right)^k\times\left(1-\frac{1}{f}\right)^{N-k} \tag{3}$$

A tag can be successfully identified only when its corresponding slot is a singleton slot or a resolvable k-collision slot. The probability that the slot is a resolvable k-collision slot can be written as

$$P' = k! \times \left(\frac{1}{k}\right)^k \tag{4}$$

Let P_{c_r} denote the probability that k tags in the same collision slot are mapped to different positions in the string (i.e. probability that the collision slot can be solved), which can be written as

$$P_{c\_r} = P_c \times P' = \sum_{k=2}^{N}\frac{k!}{k^k}\binom{N}{k}\times\left(\frac{1}{f}\right)^k\times\left(1-\frac{1}{f}\right)^{N-k} \tag{5}$$

According to (2) and (5), the probability that the tag can be successfully identified is P, which can be written as

$$\begin{aligned} P &= P_1 + P_{c\_r} \\ &\approx \frac{N}{f}\times e^{-\frac{N}{f}} + \sum_{k=2}^{N}\frac{N(N-1)...(N-k+1)}{k^k}\left(\frac{1}{f}\right)^k\times e^{-\frac{N}{f}} \end{aligned} \tag{6}$$

Let S_1 denote the number of expected singleton slots and S_{c_r} denote the number of expected resolvable collision slots, respectively. They are given as follows

$$S_1 = f \times P_1 \approx N \times e^{-\frac{N}{f}} \tag{7}$$

$$S_{c\_r} = f \times P_{c\_r} \approx f \times \sum_{k=2}^{N}\frac{N(N-1)...(N-k+1)}{k^k}\left(\frac{1}{f}\right)^k\times e^{-\frac{N}{f}} \tag{8}$$

According to (7) and (8), we can calculate the number of tags in each singleton slot $N_1$and the number of tags in each resolvable collision slot N_{c_r}, respectively. They are given as follows

$$N_1 = S_1 \approx N \times e^{-\frac{N}{f}} \tag{9}$$

$$\begin{aligned} N_{c\_r} &= f \times \sum_{k=2}^{N} k \times \frac{k!}{k^k}\binom{N}{k}\times\left(\frac{1}{f}\right)^k\times\left(1-\frac{1}{f}\right)^{N-k} \\ &\approx f \times \sum_{k=2}^{N}\frac{N(N-1)...(N-k+1)}{k^{k-1}}\left(\frac{1}{f}\right)^k\times e^{-\frac{N}{f}} \end{aligned} \tag{10}$$

Let N_{total} denote the total number of tags that can be successfully identified in each round. Which can be calculated as

$$N_{total} = N_1 + N_{c\_r} \tag{11}$$

The execution time T_1 of the first part consists of two parts: the time to broadcast the main filter vector F and the time to deactivate known tags. Therefore, we have

$$\begin{aligned} T_1 &= \left\lceil \frac{f}{96} \right\rceil \times t_{tag} + N_{total} \times t_s \\ &\approx \frac{t_{tag}}{96} + [N \times e^{-\frac{N}{f}} + f \sum_{k=2}^{N} \frac{N(N-1)\ldots(N-k+1)}{k^{k-1}} \left(\frac{1}{f}\right)^k \times e^{-\frac{N}{f}}] \times t_s \end{aligned} \tag{12}$$

According to (11) and (12), the average time for verifying the presence of one tag is given as follows

$$\begin{aligned} \theta &= \frac{T}{N_{total}} = \frac{\left\lceil \frac{f}{96} \right\rceil \times t_{tag} + (N_1 + N_{c\_r}) \times t_s}{N_1 + N_{c\_r}} \\ &\approx \frac{\frac{t_{tag}}{96} + (\alpha \times e^{-\alpha} + \frac{1}{k^{k-1}} \times \alpha^k \times e^{-\alpha}) \times t_s}{\alpha \times e^{-\alpha} + \frac{1}{k^{k-1}} \times \alpha^k \times e^{-\alpha}} \end{aligned} \tag{13}$$

According to the existing work [25]–[30], t_{tag} and t_s are set to 2.4ms and 0.4ms, respectively. By analyzing formula (13), we can know that the average time θ for verifying a tag is a function related to α(where $\alpha = N/f$). From the curve in Fig. 4, we can know that when $\alpha \approx 1.42$, θ is at a minimum value of approximately 0.4509ms. Thus, we can know the optimal frame length $f = N/1.42$. Where N is the set of expected tags in total.

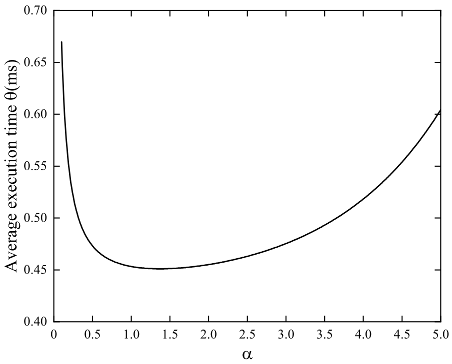


Fig. 4. The average execution time for verifying a tag with respect to $\boldsymbol{\alpha}$.

We assume that there are U unknown tags in the scene, the time required for the second part is determined by broadcasting additional vector A. Let $P_c{}'$ represent the probability that there is an actual collision slot among all considered slots, which can be written as

$$\begin{aligned} P_c{}' &= 1 - P_1{}' - P_0{}' \\ &= 1 - \begin{pmatrix} N+U \\ 1 \end{pmatrix} \times \frac{1}{f} \times \left(1 - \frac{1}{f}\right)^{N+U-1} - \left(1 - \frac{1}{f}\right)^{N+U} \\ &\approx 1 - \frac{N+U}{f} \times e^{-\frac{N+U}{f}} - e^{-\frac{N+U}{f}} \end{aligned} \tag{14}$$

Further, we can obtain the length L_A set by the additional vector A, where S' represents the number of collision slots after the actual mapping. Therefore, we have

$$\begin{aligned} L_A &= \sum_{k=2}^{N+U} S' = \sum_{k=2}^{N+U} f \times P_c{}' \\ &\approx \sum_{k=2}^{N+U} f - (N+U) \times e^{-\frac{N+U-1}{f}} - f \times e^{-\frac{N+U}{f}} \end{aligned} \tag{15}$$

The execution time of the second part T_2 consists of the time to broadcast additional vector A, which can be written as

$$\begin{aligned} T_2 &= \left\lceil \frac{L_A}{96} \right\rceil \times t_{tag} \\ &\approx \left\lceil \frac{\sum_{k=2}^{N+U} f - (N+U) \times e^{-\frac{N+U-1}{f}} - f \times e^{-\frac{N+U}{f}}}{96} \right\rceil \times t_{tag} \end{aligned} \tag{16}$$

In the third part, we need to resend the length of the main filter vector F and verify unknown tags. Therefore, we can get the execution time T_3 of the third part, which can be written as

$$T_3 = \left\lceil \frac{f}{96} \right\rceil \times t_{tag} + U \times t_{tag} \tag{17}$$

According to (12), (16), and (17), we can get the total execution time T_{total} of BTUTI, Which can be calculated as

$$\begin{aligned} T_{total} &= T_1 + T_2 + T_3 \\ &= \left\lceil \frac{2f}{96} \right\rceil \times t_{tag} + \left\lceil \frac{L_A}{96} \right\rceil \times t_{tag} + N_{total} \times t_s + U \times t_{tag} \end{aligned} \tag{18}$$

Further, we can get the time efficiency ζ of protocol execution, where $\kappa = \alpha \times e^{-\alpha} + \frac{1}{k^{k-1}} \times \alpha^k \times e^{-\alpha}$. ζ can be written as

$$\begin{aligned} \zeta &= \frac{N_{total} \times t_s}{T_{total}} = \frac{(N_1 + N_{c\_r}) \times t_s}{\left\lceil \frac{2f}{96} \right\rceil \times t_{tag} + \left\lceil \frac{L_A}{96} \right\rceil \times t_{tag} + N_{total} \times t_s + U \times t_{tag}} \\ &\approx \frac{\kappa \times t_s}{\left(1 + \left\lceil \frac{\sum_{k=2}^{N+U} 1 - (N+U-1) \times e^{-\frac{N+U-1}{N}\alpha}}{96} \right\rceil\right) \times t_{tag} + \kappa \times t_s + \frac{U}{N} \times \alpha \times t_{tag}} \end{aligned} \tag{19}$$

V. PERFORMANCE EVALUATION

In this section, we simulate BTUTI in MATLAB 2016 on an HP ProDesk 480 G6 MT with an Intel 3.0GHz CPU. We compared the proposed BTUTI protocol with existing BUIP [30], FUTI [31], LUTI [35], HUTI [35], and EUTI [36] schemes in terms of execution time, total number of slots, and time efficiency, respectively.

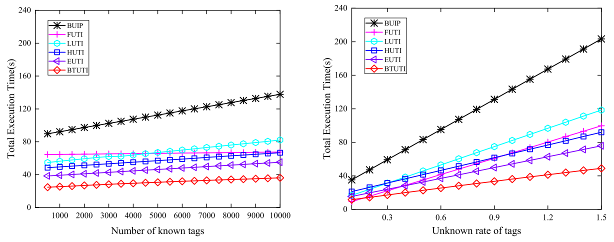
A. Simulation Settings

According to the current EPC Class1 Gen-2 standard, the tag memory stores a unique ID of 96 bits that represents its identity. We assume that the communication between tags and readers is not blocked by obstacles. The problem of missing tag reading due to the different communication rates between readers and different tag responses are not considered. Eliminate energy loss during communication. In the simulation setting, we set the rate of both reader and tag to be $40kb/s$, and the time required to transmit 1 bit of data between them is $25\mu s$. Therefore, we set the t_{tag} length that allows the transmission of tag ID as 2.4ms and t_s length that contains only 1 bit of information as 0.4ms. The result of each experiment is the average value obtained by running 1000 simulations.

B. Impact of Number of Known Tags

According to the definition of existing work [30]–[32], [34]–[36], it guarantees the efficient implementation of the identification process by finding the optimal execution time. Therefore, we compare our protocol with the existing work in Fig. 5(a). We first consider the effect of known tags on recognition time. Specifically, we fix U=10000 and set 10,000 known tags for the experiment, while the known tags increase at a rate of 0.05 times.

For example, when N=10000, the execution time of BUIP, FUTI, LUTI, HUTI, and EUTI are 137.78, 67.5, 82.1, 66.67, and 55.08 seconds, respectively. In contrast, the execution time of BTUTI proposed in this paper is 36.06 seconds, which is 73.8%, 46.57%, 56.07%, and 45.9% higher than existing schemes. It can be seen that there is also an improvement of 34.53% compared with the existing better EUTI scheme. The reason is that BTUTI reduces execution time by effectively using some collision slots to validate multiple tags.



(a) (b)

Fig. 5. Effects of known and unknown Tags on total execution time: (a) U=10000, when varying N from 500 to 10000, (b) N=10000, when varying the unknown rate of tags from 0.1 to 1.5.

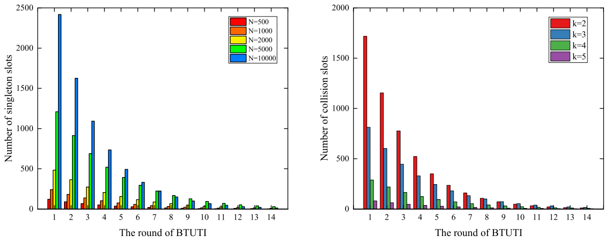
C. Impact of Unknown Rate

As shown in Fig. 5(b), we consider the impact of unknown tags on execution time. Specifically, we fix N=10,000 and set the unknown tag ratio to vary between 0.1 and 1.5 for experiment, increasing at a rate of 0.1 times.

For example, when the unknown tag ratio is set to 1.5, the execution times of the BUIP, FUTI, LUTI, HUTI, and EUTI are 203.29, 99.64, 118.47, 91.92, and 75.72 seconds, respectively. In contrast, the execution time of the BTUTI proposed in this paper is 48.95 seconds, which is 75.9%, 50.87%, 58.68%, and 46.7% higher than existing schemes. It can be seen that there is also an improvement of 35.35% compared with the existing better EUTI scheme. The underlying reasons are as follows. In BUIP, known tag and unknown tag reply in the same slot, which will lead to the inability to identify the tag in this slot, further increasing the execution time. In FUTI, LUTI, and HUTI, tags are deactivated by checking for the presence of known tags in singleton slot of each expected frame. However, the known tag will be disturbed by the unknown tag in the process of replying to the reader, which will waste these slots and increase the execution time. The EUTI uses the reservation mechanism to skip idle slots in the unknown tag identification phase, which reduces execution time. However, unknown tags in collision slots cannot be identified. In BTUTI, through the use of collision slots, part of the collision slots can be turned into a singleton slot, thus increasing the ratio of singleton slots and further deactivating more known tags. Therefore, the time to broadcast the vector multiple times is reduced.

D. The Utilization Ratio of Slot

Fig. 6 shows the number of single slots and collision slots in each round of identification of the BTUTI protocol. Considering the impact of unknown tags on the identification process, which will increase the number of execution rounds. Therefore, we fixed U=500 for experiments. As shown in Fig. 6(a), the number of singleton slots will continue to decrease with the identification process until all known tags are silent. Fig. 6(b) shows the number of different k-collision slots. We set N=10000 for the experiment. With the increase of the k value, the corresponding k-collision slots of each round decrease.



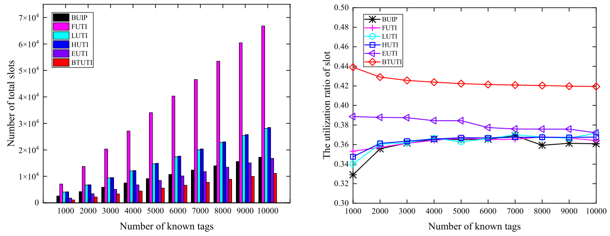
(a) (b)

Fig. 6. Changes in the number of singleton slots and collision slots in each round of BTUTI: (a) U=500, when varying N from 500 to 10000, (b) N=10000 with different values of k.

Then we compared the total number of time slots in different schemes after all known tags were identified, where total slots is the sum of the non-empty slots required for each round. Similarly, we set 10000 known tags for the experiment, while the known tags increase at a rate of 0.1 times. The experimental results are shown in Fig. 7(a).

For example, when N=10000, the total number of slots for BUIP, FUTI, LUTI, HUTI, and EUTI are 17,208, 66816, 28087, 28457, and 16800 respectively. In contrast, the number of total slots for BTUTI is 11120. Compared with the existing scheme, the increases were 35.37%, 83.35%, 60.4%, 60.92%, and 33.8%, respectively. In FUTI, the frame length is set to the number of tags. Compared to BUIP, LUTI, HUTI, and EUTI, BTUTI can verify multiple tags in collision slots, which reduces some execution slots. The BTUTI protocol significantly improves the utilization of slots by setting the optimal frame length.

Fig. 7(b) shows the time slot utilization of different methods. We can see that the BUIP, FUTI, LUTI, and HUTI protocols are maintained at 36% of time slot utilization because it does not utilize the generated collision slots. In EUTI, it can separate a known tag from a plurality of tags from multiple tags, thereby improving the utilization of the slot, but only a partial collision time slot is utilized. In the BTUTI protocol, tags in collision slots are mapped to make more collision slots into coordinated slots, thereby increasing the utilization of time slots. BTUTI can increase by 10.6% compared to the EUTI protocol.



(a) (b)

Fig. 7. Comparison of different methods in the total number of slots and the utilization ratio of slot: (a) U=500, when varying N from 1000 to 10000, (b) U=500, when varying N from 1000 to 10000.

E. Time Efficiency When Varying Known Tags

The time efficiency of these methods is closely related to the number of known tags. Therefore, we fix U=500 and set 20,000 known tags for the experiment, while the known tags increase at a rate of 0.05 times. Fig. 8 shows the time efficiency comparison between our scheme and the existing scheme. Compared with existing BUIP, FUTI, LUTI, HUTI, and EUTI, it is 89.87%, 21.75%, 36.17%, 72.9%, and 28.9% higher, respectively. We can see an improvement of 28.9% compared to the current best protocol as well. The results show that the BTUTI protocol has great advantages in time efficiency. Existing schemes are designed to reduce the impact of known tags on the identification process, where the BUIP uses three different commands to distinguish the tag state, which increases the transmission overhead. While FUTI, LUTI, HUTI, and EUTI protocols use filtering to reduce a part of the interference of known tags, and also need to transmit multiple filtering results, which increases the execution efficiency. However, In the BTUTI protocol, all collision slots are hashed again through bit tracking, which can improve the utilization rate of slot and reduce the transmission overhead, and further improve the execution efficiency of existing methods.

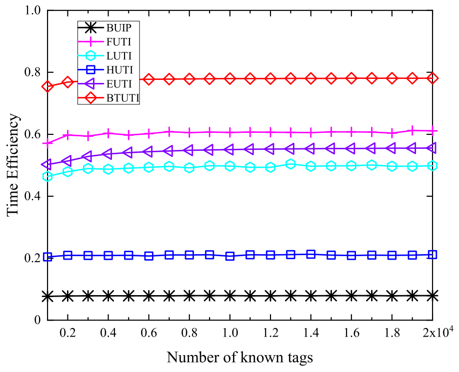


Fig. 8. Comparison of various methods in time efficiency.

VI. CONCLUSION

In this paper, we study the problem of identification efficiency in large RFID warehouse management systems. In fact, there may be the tag that is incorrectly placed outside its recognition range. How to effectively identify these unknown tags is the problem to be solved in this paper. However, the existing work has the disadvantages of incomplete identification of unknown tags and low time efficiency. To manage the warehouse efficiently, we propose a Bit-Tracking Based Strategy for Unknown Tag Identification (BTUTI) protocol. This protocol changes a part of the collision slots into coordinated collision slots by hashing collision tags again. In the tag verification stage, we directly skip empty slots and uncoordinated collision slots, thus improving time efficiency and slot utilization. Experimental results show that BTUTI is superior to existing schemes in execution time, total number of slots, and time efficiency.

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