One More Hash is Enough: Efficient Tag Stocktaking in Highly Dynamic RFID Systems

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***Abstract*—An RFID system can greatly improve the efficiency of tagged object inventory setup and update. It is necessary to periodically take stock of tags and update the inventory accordingly (i.e., deleting absent tags and adding new tags) in dynamic scenarios such as warehouses and shopping malls. Fast tag stocktaking is critical for the dynamic RFID system management. Previous work can take stock of tags by either collecting IDs of all the tags in the system, which is known to be inefficient, or broadcasting a long indicator vector to save tag identification time, which is not compatible with current commercial-off-the-shelf (COTS) tags. In this paper, we propose HARN, a protocol that can quickly take stock of tags in dynamic RFID systems but is compatible with COTS RFID tags and easily applied in a real RFID system. HARN uses only one more hash in the standard EPC C1G2 protocol. It leverages the new hash to generate the random number (RN) for a tag that can be used for both channel contention and known tag recognition, which can save the tedious ID transmission from known tags to readers and greatly speed up the stocktaking of tags. Simulation results demonstrate that HARN improves stocktaking throughput by up to 3.8x when compared to the state-of-the-art solutions in dynamic RFID systems.**

I. Introduction

Nowadays, Radio Frequency IDentification (RFID) is widely used in many applications including supply chain monitoring, warehouse management, inventory control, etc. In these applications, physical objects are attached with RFID tags that have unique IDs and can store private information of objects. The information stored in tags is then scanned by readers through the wireless channel and sent to a backend server for automatic object management. According to a recent forecast report given by IDTechEx [1], the total RFID market will be worth $30.24 billion by 2024.

Periodical stocktaking of tags is an important and essential operation in RFID system management. For example, warehouses or shopping malls have to periodically take stock of the products and update the product inventories accordingly. However, traditional tag identification protocols aim to collect IDs of all the tags in the system [2]–[6], and are thus very inefficient in dynamic RFID systems in which only a fraction of tags move in or move out during two consecutive stocktaking operations. For example, assume that there are 1000 tags in the system and only 200 of them are *fresh tags*, i.e., tags that entered the system after the last stocktaking operation and have not been identified yet. Only the 200 fresh tags need to be identified. The other 800 tags whose IDs have already been collected, referred to as *known tags* hereinafter, need not to be identified again. However, traditional tag identification protocols identify all the 1000 tags from scratch, resulting in low time efficiency in tag stocktaking.

Although there are already some solutions to fresh tag identification in dynamic RFID systems [7]–[11], they mainly suffer from two problems. First, they use some techniques that require high computational and storage ability at the tag side, e.g., *indicator vector* [12]. Such techniques require significant modifications to the current commercial-off-the-shelf (COTS) tags and are difficult to implement. Second, when identifying fresh tags, existing solutions require that no known tags leave the system (i.e. no tags are missing) during two consecutive stocktaking operations. Thus they cannot well handle the *hidden tag* problem in systems where known tags may move out. For example, a fresh tag may appear to be the same as a left known tag and thus cannot be recognized and identified.

In this paper, we present an efficient tag stocktaking protocol in highly dynamic RFID systems. Aiming to provide a stocktaking solution that can be easily implemented on COTS tags, we design a novel method that can efficiently distinguish fresh tags from known tags with only minimum modifications at the tag side. We use a novel hash-based method to build connections between a tag's *Random Number* (RN) field and its tag ID. With such connections, the RN field can be used for fresh/known tag recognition as well as channel contention, while in the current tag identification standards it can be used for channel contention only. We thus propose a tag stocktaking protocol with ***HA***sh-based ***RN*** generation, namely HARN. HARN effectively improves identification throughput of fresh tags in dynamic RFID systems and can well handle the hidden tag problem. Simulation results demonstrate that HARN improves the stocktaking throughput by up to 3.8x with respect to fresh tags when compared with state-of-the-art solutions.

The rest of the paper is organized as follows. Section II introduces some background on RFID identification and gives the problem statement. Section III presents the design and analysis of HARN. Evaluation results based on simulation experiments are reported in Section IV. Section V reviews related work. Finally, Section VI concludes the paper.

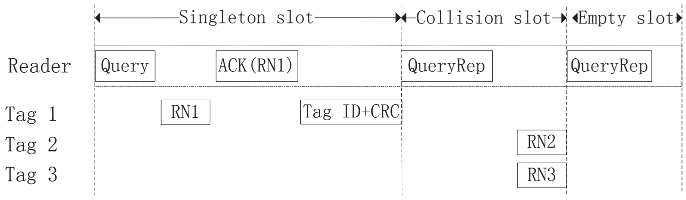


Fig. 1. Illustration of the standard EPC C1G2 protocol.

II. Background and Problem Statement

A. Revisiting EPC C1G2 Protocol

EPC C1G2 protocol [13] is a popular tag identification standard and is adopted by most commercial-off-the-shelf (COTS) tags. In the protocol, the reader issues a series of frames (also called query rounds) to identify tags. A frame contains a number of synchronized slots, and each tag randomly selects one slot in the frame to reply to the reader. In this paper, we name the process to identify all the tags as *an identification operation*. Each identification operation consists of multiple *frames*, and each frame consists of many synchronized *time slots*.

To start a frame, the reader broadcasts a *Query* command to tags containing a parameter f, indicating that there are f slots in the frame. Upon receiving the Query command, each tag picks a random value in the range $[0, f-1]$, and loads the value into its slot counter. The reader then broadcasts a *QueryRep* command in each following time slot to identify tags, as shown in Fig. 1. A tag decreases its slot counter by 1 every time when it receives the QueryRep command from the reader. Meanwhile, every tag generates a 16-bit random number, namely *RN*, by using a random number generator. If a tag, in response to the Query or QueryRep command, finds that its slot counter value is zero, it backscatters its RN field to contend for the channel access.

There are three different types of slots, as illustrated in Fig. 1. When only one tag backscatters its RN to the reader, the reader can successfully receive the RN. In this case, the reader immediately broadcasts an *ACK* containing the just received RN. The corresponding tag, finding that the RN piggybacked in the ACK command equals its own RN, will transmit its ID to the reader. The tag then enters the *acknowledged* state and will exit the current identification operation. Such a slot is called a *singleton slot*. If more than one tag simultaneously transmit their RNs in a slot, the reader will detect a collision. Such a slot is called a *collision slot*. A slot in which no reply is received is called an *empty slot*. Only singleton slots can be used to identify tags in the EPC C1G2 protocol.

In the standard EPC protocol, the only purpose of a tag's RN field is to contend for channel access. An RN does not relate to a tag ID – When the reader receives a RN, it has to further receive the tag ID to identify a tag. *We observe that if the reader can judge whether a received RN is from a known tag or a fresh tag, then the reader can greatly improve its identification throughput of fresh tags.*

B. Statement of The Problem

We consider a RFID system that consists of N known tags $KT = \{t_1, t_2, \ldots, t_N\}$ and M fresh tags $FT = \{u_1, u_2, \ldots, u_M\}$. The reader knows IDs of known tags and has to collect IDs of fresh tags. Because the system is dynamic, KT might change frequently in different identification operations. It is also possible that some known tags recorded in KT have already left the system after the last identification operation. These tags are usually termed as *missing tags* [14]–[16]. Different from previous fresh tag identification protocols that do not allow missing tags [7], [9]–[11], we allow the *existence of missing tags*. That is, our protocol does not require all the tags recorded in KT are present in the system during the stocktaking operation.

The problem to be solved in the paper is how to quickly take stock of all the tags in the system with the tag IDs collected in the last stocktaking operation as known knowledge. The aim is to design an efficient tag stocktaking protocol that requires only minimum modification to the EPC C1G2 specification, i.e., using only mandatory abilities that must be implemented by current COTS tags such as *hashing* and *random number generating*. A simple *Baseline* solution to this problem is to identify all the tags in the system with existing tag identification protocols. In contrast, a best solution is to collect the IDs of only the fresh tags (i.e. tags in FT), and meanwhile figures out which tags recorded in the database are missing. We call this solution as the *Ideal* solution.

III. Design of HARN

This section first presents the design of the HARN protocol, then analyzes how to set the optimal parameters to maximize identification throughput of fresh tags, and finally discuss its ability to handle the hidden tag problem.

A. Hash-based Approach to Generating RN

In the original EPC C1G2 protocol, tags use their RNs to contend for channel access. A tag's RN field is independent of its ID. Thus, the reader cannot differentiate whether a received RN is from a known tag or from a fresh tag, even in the case that it knows the IDs of known tags. If the received RN can be used to distinguish known tags and fresh tags, the reader can identify only fresh tags and avoid wasteful re-identification of known tags.

Our solution is to generate the RN field for a tag by hashing its ID to a value in the range $[0, 2^{16}-1]$. Tag t's RN is generated as $RN_t = H(ID_t) \mod 2^{16}$, where ID_t is t's tag ID and H is a common hash function known to both the reader and the tag. With this method, the reader can predict what RN it will receive if a known tag transmits. Furthermore, as the value of t's slot counter is calculated according to its RN filed [13], *the reader can predict in which slot a known tag will backscatter its RN*. Thus, when the reader receives a RN that is different from corresponding known tag's RN, it knows that the RN must be from a fresh tag and can collect its ID immediately.Besides the original RN used to for channel contention, we introduce the second RN

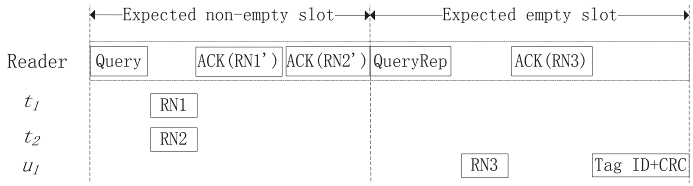


Fig. 2. Illustration of the HARN protocol.

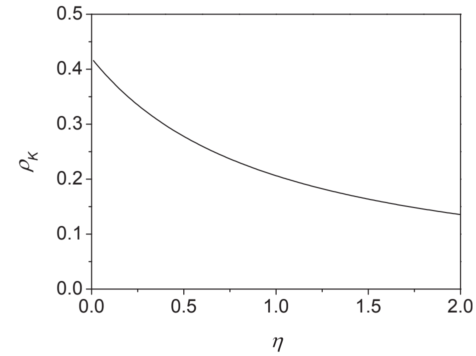


Fig. 3. Optimal ρ_K in the first frame of HARN for different η.

to help quickly suppress responses from known tags. For tag t, its second RN is generated as $RN_t' = H(ID_t^r) \mod 2^{16}$, where ID_t^r is the reverse of ID_t. It should be guaranteed that $RN_t' \neq RN_t$. If the two generated RNs are equal, we let $RN_t' = RN_t + 1$.

The purposes of RN and RN' are threefold. First, as same as in the original EPC C1G2 protocol, a tag uses its RN field to contend for channel access. Second, the reader uses the RN field to distinguish fresh tags from known tags. Third, the reader uses RN' to suppress responses from known tags. We explain how to achieve these purposes in the next section.

B. Description of The HARN Protocol

HARN follows the framework of the original EPC protocol but makes some slight changes to quickly suppress responses from known tags. In HARN, the first frame is special and is different from following frames: It is used to suppress all the known tags to make them enter the acknowledged state. Except the first frame, the other frames of HARN are exactly the same as in the original EPC C1G2 protocol.

Before starting the first frame, the reader calculates the expected status of every slot in the frame according to the IDs of known tags. Recall that the reader knows which slot a known tag t_i will pick up because it knows t_i's ID. It then predicts which RNs it will receive from known tags in each slot. As shown in Fig. 2, the reader acts as below for each slot:

- If no known tag will respond in the slot (i.e. in an *expected empty slot*), the reader acts as the same as in the standard EPC protocol. In this slot, any RNs must be from fresh tag(s). If the reader receives a RN successfully, it broadcasts an ACK command containing the received RN. Otherwise, if the reader receives no signal or detects a collision, it simply broadcasts a QueryRep command to move to the next slot.
- If in a slot where at least one known tag will respond (i.e. in an *expected non-empty slot*), the reader sends a series of ACK commands to suppress known tags mapped to this slot. Assume that k known tag $\{t_1, \ldots, t_k\}$ select this slot. For each tag t_i ($1 \leq i \leq k$), the reader broadcasts an ACK command containing *t_i's second random number (RN')* to suppress its participation in the current identification operation.

Upon receiving commands, tags act as below:

- When tag t receives a Query/QueryRep command and its slot counter equals zero in response to the received command, it backscatters RN_t to the reader.
- If the tag receives an ACK command containing the same RN as its first RN, it transmits its tag ID along with the CRC to the reader and then enters the *acknowledged* state.
- If the tag receives an ACK command containing a RN field that is different from its first RN but equals to its second RN, it also enters the *acknowledged* state.

Missing Tag Detection: In expected non-empty slots, the reader also detects if there are any missing tags. For each known tag t_i selecting this slot, the reader detects whether t_i' RN signal appears in the received signal by performing a cross correlation [17] between the received signal and t_i's RN signal, which could be recorded when identifying t_i or locally generated by using t_i's RN value. Existence of a peak value means that t_i's signal is in the received signal. With this approach, missing tags can be detected.

C. Minimizing Per Fresh Tag Identification Time

We now discuss how to set the length of the first frame to minimize the average time to identify a fresh tag. Except the first frame, the other frames in HARN adopt the same frame size setting strategy as in traditional tag identification protocols.

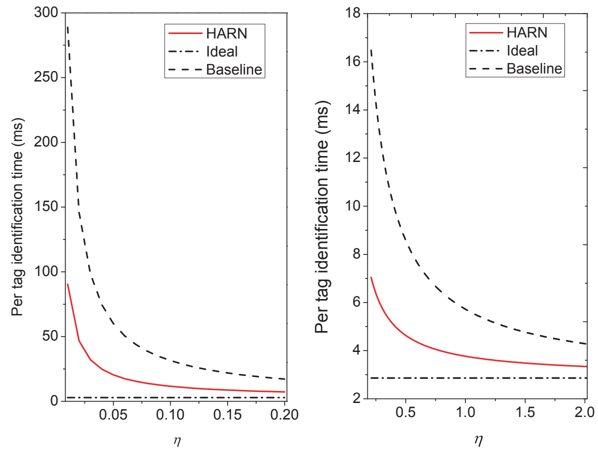
1) The First Frame: Besides identifying fresh tags, the main purpose of the first frame is to suppress responses from all the known tags. Assume that the frame size is f. We use N_e to denote the number of expected empty slots in the frame, and use N_s to denote the number of slots in which fresh tags are successfully identified. The total duration of the frame is

$$T = T_{id} * N_s + T_e * (N_e - N_s) + N * T_{ack} + (f - N_e) * T_{qrn}, \quad (1)$$

where T_{id} and T_e indicate the duration of a single slot and an empty slot, T_{ack} indicates the time to send an ACK command containing a RN field, and T_{qrn} represents the time needed to send a Query plus a RN, respectively. The third term in equation (1) indicates the time spent in suppressing known tags by sending ACK commands in expected non-empty slots, and the fourth terms indicates the time spent in receiving RNs transmitted by tags.

As there are N known tags and M fresh tags, N_s and N_e can be calculated as

$$N_e \approx f * e^{-N/f}, N_s \approx M * e^{-(M+N)/f}. \quad (2)$$



(a) Small η (b) Large η

Fig. 4. Average time to identify a fresh tag in the first frame of HARN.

Then the average time to identify a fresh tag is

$$T_f = \frac{T}{N_s} = T_{id} + T_e * (\frac{N_e}{N_s} - 1) + T_{ack} * \frac{N}{N_s} + T_{qrn} * \frac{f - N_e}{N_s}. \quad (3)$$

We define the ratio of fresh tags to known tags as $\eta = M/N$, and define the load factor with respect to known tags as $\rho_K = N/f$. Then we have

$$T_f = T_{id} + T_e(\frac{e^{\eta\rho_K}}{\eta\rho_K} - 1) + \frac{T_{ack}}{\eta} e^{(1+\eta)\rho_K} + T_{qrn} \frac{e^{(1+\eta)\rho_K} - e^{\eta\rho_K}}{\eta\rho_K} \quad (4)$$

To minimize T_f, we let $\frac{\partial T_f}{\partial \rho_K} = 0$, and know that the minimum value of T_f is attained when

$$T_e \frac{e^{\eta\rho_K}(\eta\rho_K - 1)}{\eta\rho_K} + T_{ack} \frac{e^{(1+\eta)\rho_K}(1+\eta)}{\eta} + T_{qrn} \frac{\rho_K e^{(1+\eta)\rho_K} + (\eta - 1)(e^{(1+\eta)\rho_K} - e^{\eta\rho_K})}{\eta\rho_K^2} = 0. \quad (5)$$

Fig. 3 plots the optimal ρ_K to minimize T_f for different η according to the time specification in the EPC C1G2 standard [13]. It can be observed that ρ_K decreases when η increases, which means that a longer frame should be used when there are more fresh tags in the system.

Fig. 4 plots T_f in the first frame of HARN and compares it with the Baseline and the Ideal solution. It can be observed that T_f decreases when η increases. When η increases, a longer frame is used as shown in Fig. 3, and more fresh tags could be identified in the first frame. This means that the overhead in suppressing known tags are amortized by more fresh tags, and thus the per fresh tag identification time is reduced. Compared with the Baseline solution, HARN reduces per tag identification time by up to 58 percent. We should point out that only a small fraction of fresh tags ($e^{-(1+\eta)\rho_K}$) are identified in the first frame, and the other fresh tags are identified without interference from known tags in the following frames. Thus the per tag identification time averaged over all the fresh tags is low, as to be shown in Section IV.

D. Probability of Hidden Tags

It is possible that some fresh tags might be incorrectly suppressed in the first frame and thus cannot be identified successfully. We call such tags as *hidden tags* as they seem to be "hidden" by the protocol. The hidden tag problem is a common problem that torments all previous protocols targeting fresh tag identification [7]–[11]. We now calculate the probability that a fresh tag is a hidden tag in HARN.

In HARN, a fresh tag t is incorrectly suppressed and becomes a hidden tag when it meets two conditions: 1) It selects an expected non-empty slot, and 2) Among the known tags selecting the same slot of t, at least one known tag's second RN equals t's second RN. We use P_h to denote the probability that t is incorrectly suppressed, and use $P_{h|k}$ to denote the conditional probability that t is suppressed when there are exactly k known tags selecting the same slot of t. The we have

$$P_h = \sum_{k=1}^{N} P_k * P_{h|k}, \quad (6)$$

where P_k denotes the probability that exactly k known tags select the same slot as t, and can be calculated as

$$P_k = \binom{N}{k} (\frac{1}{f})^k (1 - \frac{1}{f})^{N-k}. \quad (7)$$

To calculate $P_{h|k}$, we consider the expected number of distinct RN's when k known tags choose their RN's independently in the range $[0, 2^{16} - 1]$, which is denoted as E_k. Actually, E_k equals the expected number of non-empty slots in a frame containing $Q = 2^{16}$ slots when k tags choose their slots independently, which is

$$E_k = Q(1 - (1 - \frac{1}{Q})^k) \approx Q * (1 - e^{-k/Q}). \quad (8)$$

In practice, k is far less than Q, in which case $E_k \approx k$. Thus,

$$P_{h|k} = \frac{E_k}{Q} \approx \frac{k}{Q}. \quad (9)$$

Substituting equation (7) and equation (9) into equation (6), we have

$$P_h = \frac{N}{Q * f} \sum_{k=1}^{N} \frac{(N-1)!}{(k-1)!(N-k)!} (\frac{1}{f})^{k-1} (1 - \frac{1}{f})^{N-k} \le \frac{N}{Q * f} = \rho_K * \frac{1}{Q}. \quad (10)$$

As ρ_K is determined by η, P_h is also determined by η. Fig. 5 plots P_h for different η. It shows that P_h decreases when η increases, and it is always smaller than 10^{-5}. This means that HARN can well handle the hidden tag problem in real RFID systems, even when there are thousands of fresh tags in the reader's interrogation region.

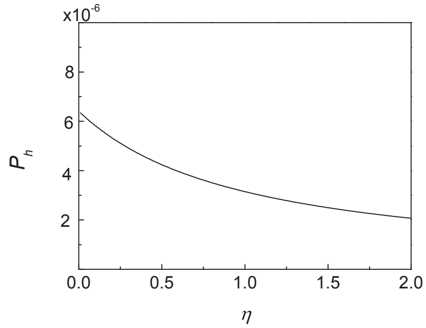


Fig. 5. Probability of hiding fresh tags in HARN for different η.

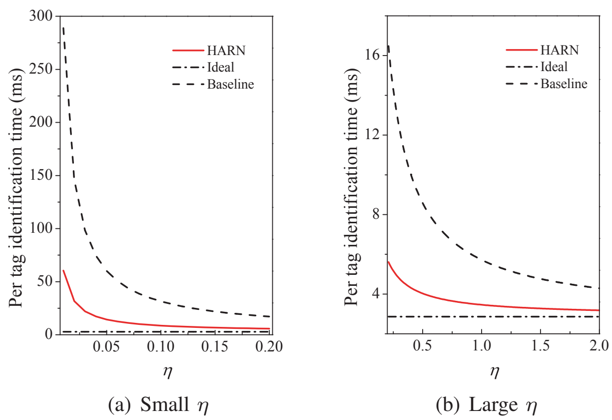


Fig. 6. Average identification time for different η.

IV. Performance Evaluation

We evaluated the performance of HARN by using a simulator developed with Matlab. We mainly compare the performance of our protocols with Baseline and Ideal, as they are the only solutions that require no significant modifications to current COTS tag specification. We also compare HARN with the IFUTI protocol [11] that represents state-of-the-art solutions based on indicator vector. The execution time of different protocols are calculated according to the EPC C1G2 UHF tag specification [13] when the data rate between the reader and tags is set at 62.5 Kbps.

A. Impact of The Ratio of Fresh Tags

Fig. 6 plots the per tag identification time *averaged over all the fresh tags* in different protocols. The advantages of HARN are significant when η is small. Compared with Baseline, HARN reduces per tag identification time by at most 79 percent. This respectively reflects about 3.8x increase in identification throughput with respect to fresh tags. Moreover, HARN performs better when η is larger. For example, the performance of HARN is very close to that of the Ideal solution when $\eta \geq 0.7$, showing its superior performance in highly dynamic RFID systems.

B. Comparison with Non-compatible Solutions

We also compare HARN with those solutions that are not compatible with current COTS tags to show the superior performance of our protocols. IFUTI [11] is a probabilistic approach to fresh tag identification that leverages a filter vector broadcasted by the reader to suppress responses from known tags. Fig. 7 plots per tag identification time in different protocols when η is small. HARN performs better than IFUTI, and the relative improvement factor increases when η increases. Compared with IFUTI, HARN reduces per tag identification time by at most 32 percent, which is equivalent to 47% increase in identification throughput. When η is large, as shown in Fig. 8, HARN performs much better than IFUTI. In average, compared with IFUTI, HARN reduces per tag identification time by around 60%, which is equivalent to about 1.5x increase in identification throughput. Compared with the Ideal solution, HARN uses only about 25% more time to identify a tag when η is large.

V. Related Work

Early works on RFID tag identification focus on collecting IDs of all the tags in the system. They can be classified into two categories [18]: ALOHA-based protocols and tree-based protocols. In [6], [19] and [2], the authors investigated optimization of time efficiency and energy efficiency, respectively, by adjusting frame size in ALOHA-based tag identification protocols. In [5], the authors proposed an adaptive tree traversal method to improve time efficiency of tree-based protocols. The DDC protocol [3] uses a specially designed RN pattern with which two colliding RN signals could be separated, which improves identification throughput. The F-CAT protocol proposed in [4] uses analog network coding (ANC) [20] to separate tag IDs from mixed signals received in collision slots. Both DDC and FCAT cannot distinguish fresh tags from known tags, and suffer from performance degradation in RFID systems where only a part of tag IDs need to be identified. Compared with them, our protocol greatly improve identification throughput of fresh tags by avoiding re-identification of known tags.

Some efforts have been devoted to improve identification throughput with respect to fresh tags [7]–[11]. Continuous scanning [7] is the first work on suppressing responses of known tags to speed the identification of fresh tags. However, it needs modification of the standard EPC C1G2 protocol

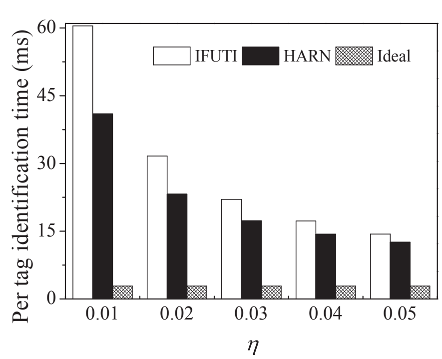


Fig. 7. Comparison with IFUTI [11] when η is small.

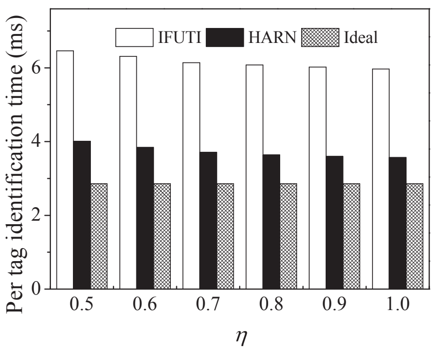


Fig. 8. Comparison with IFUTI [11] when η is large.

and is not compatible with COTS tags. MUIP [9], [10] can guarantee collecting IDs of all the fresh tags, but it replies on the indicator vector [12], [21] that is not supported in current COTS tags. In [8] the authors proposed an adaptive scheme to achieve high identification throughput when the rate of fresh tags varies. It also replies on the indicator vector technique. Furthermore, all these solutions requires that there are no missing tags in the system. They rely on missing tag detection algorithms [14]–[16] to find missing tags before starting their protocol. Compared with them, HARN is compatible to COTS tags and can tolerate missing tags.

Besides identifying fresh tags and missing tags, some efforts have also been devoted to misplaced tag detection [22] and tag searching [23], [24]. Bu et al. proposed several protocols to detect and localize misplaced tags using reader positions. In [23] and [24] the authors propose several tag search protocols that can detect the missing tags for a given set of tags. However, they use some techniques that are not supported by current COTS tags.

VI. Conclusion

This paper presents the HARN protocol that can boost stocktaking throughput in dynamic RFID systems. HARN is compatible with current EPC C1G2 protocol, making tags implementing HARN also coexist with current COTS tags. Simulation results demonstrate up to 3.8x increases in s-tocktaking throughput when compared with the original EPC C1G2 protocol. In the future, we plan to conduct testbed experiments to evaluate the performance of HARN by using EPC-compatible COTS tags.

Acknowledgment

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