RCSMA: Receiver-Based Carrier Sense Multiple Access in UHF RFID Systems

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Abstract—RFID tag identification is a crucial problem in UHF RFID systems. Traditional tag identification algorithms can be classified into two categories, ALOHA-based and tree-based. Both of them are inefficient due to the incidental high coordination cost. In this paper, we bring CSMA into UHF RFID systems to enhance tag read rate by reducing coordination cost. However, it is not straightforward due to the simple hardware design of passive RFID tags, which is unable to sense the transmissions or collisions of other tags. To tackle this challenge, we propose receiver-based CSMA (RCSMA) in this paper. In RCSMA, the reader notifies the tags channel condition. According to different sensing results of reader's notifications, the tags take corresponding actions, e.g., random back off. RCSMA does not require special RFID tag hardware design. An absorbing Markov chain model is presented to analyze the performance of RCSMA and shown to be consistent with the simulation results. Compared with optimized ALOHA-based algorithms and optimized tree-based algorithms, RCSMA can enhance the tag read rate by 30-70 percent under different reader and tag data rates.

Index Terms—RFID systems; CSMA; tag identification.

1 Introduction

Radio Frequency Identification (RFID) technology is widely used in managing physical assets [2], [6], [21] and indoor localization [20]. The RFID tags are labeled on items in warehouse or supermarket, so that the user can monitor or charge the items of interest. One basic issue here is tag identification [1], the process of collecting RFID tags' IDs, based on which the items can be efficiently managed. The performance of reading RFID tags plays an important role in improving the overall management efficiency. Due to the large-scale RFID tag deployment, enhancing tag identification efficiency is an important task in RFID systems [2], [4], [7], [8], [9], [10], [11], [12], [18], [19].

Nowadays, there are high coordination and collision costs (they are formally defined in Section 3) on RFID tag identification tasks due to the tag's limited functionality. In RFID systems, the RFID tags cannot self-regulate their transmissions to avoid or detect collisions. Usually, the passive tags need to be powered up by high power wireless signal and then reflect the signal to respond the reader [1], [2]. The passive RFID tag can be structured simply and cheaply owing to this feature, so that the low cost tags can be produced on a large scale.

Currently, there are two kinds of tag identification algorithms, ALOHA-based algorithm [2], [4], [7], [18], [19] and tree-based algorithm [8], [9], [10], [11], [12]. In ALOHA-based algorithms, time is divided into slots and each tag randomly transmits its ID in each time slot. The maximum throughput of ALOHA algorithm can be achieved when the frame length is equal to the number of tags. ALOHA-based algorithm has several disadvantages [2], [4], [7]. First, its performance is sensitive to the frame length (or the number of tags), e.g., all slots may be wasted if an ill-suited frame length is used. Second, the cost of collisions is extremely high. The EPC C1G2 RFID protocol [1] uses an RN16 scheme to reduce the high collision cost of tags' IDs. But RN16 itself increases the overall coordination cost. In tree-based algorithms, the reader constructs a binary tree according to the tag's ID, and then traverses this tree by broadcasting different tag ID prefix to request the tags. For each request, only the tag having the same ID prefix will make response. The EPC C1G2 RFID protocol [1] defines a Select Command to select a group of tags (have the same ID prefix) to implement a tree-based algorithm. Tree-based algorithm has several disadvantages. First, it has high coordination cost on the ID prefix sent from the reader and the overall performance drops for a lower reader data rate. Second, its performance is sensitive to the ID length (or the height of the tree). Third, its performance is sensitive to tag ID distribution [8], e.g., a "bad" distribution may drop the overall performance in orders of magnitude. Even worse, both optimized ALOHA-based algorithm (optimal frame length) and optimized tree-based algorithm (uniform ID distribution) are not able to conduct tag identification efficiently due to high coordination cost.

CSMA is considered to be a better alternative than ALOHA as it has better channel utilization (CU) (lower coordination cost). The basic idea in CSMA is that single node can sense the channel and then decide to transmit or back off according to the channel conditions [13], [14], [15], [16]. However, the tag is simply designed and incapable to

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sense other tags' transmissions [1]. Therefore, it is impossible to implement traditional CSMA protocol on passive RFID tags.

In this paper, we design receiver-based CSMA (RCSMA) to reduce the coordination cost on tag identification while preserving the simple hardware design. In RCSMA, the reader broadcasts the channel conditions and the tags "sense" the channel conditions sent from the reader. The reader notifies the tags whether transmission exists or not. We summarize the features of RCSMA as follows: first, the reader only broadcasts the channel condition in each time slot (e.g., collision occurs), which reduces the overhead of reader transmission on round initialization and RN16 scheme in EPC protocol [1]. Second, the tag maintains a contention window. It is adjusted according to the channel condition in each time slot. This design makes the contention probability fast approaching to optimum and reduces the cost of inefficient rounds in ALOHA schemes. Third, the tag only transmits an ID prefix if it decides to contend for transmission, which reduces the cost on collision and RN16 transmission.

To sum up, we make the following contributions in this paper:

- We propose a receiver-based CSMA algorithm to enhance tag read rate (TRR) by reducing coordination cost of RFID systems while preserving the simple hardware design of passive RFID tags. Compared to ALOHA-based and tree-based algorithms, RCSMA is insensitive to the number of tags and the tag ID distribution.
- We theoretically analyze performance of RCSMA using the absorbing Markov chain model. The theoretical results are compatible with those achieved by event-driven simulations.
- The extensive simulations show that RCSMA can enhance the tag read rate by 30-70 percent comparing with optimized ALOHA-based algorithms and optimized tree-based algorithms under different reader and tag data rates.

This paper is organized as follows: the related work about tag identification and CSMA in networks is summarized in Section 2. We present the detail design of RCSMA in Section 3. The theoretical analysis of RCSMA in UHF RFID systems is presented in Section 4. The evaluation is illustrated in Section 5. In Section 6, we conclude this paper and discuss the future work.

2 Related Work

The related work mainly falls into two categories, one is tag identification in RFID systems and the other is CSMA protocol in wired and wireless networks.

2.1 Tag Identification

There are two types of algorithms in tag identification: ALOHA-based [2], [4], [7], [18], [19] and tree-based [5], [8], [9], [10], [11], [12]. The EPC C1G2 UHF RFID protocol defines these two algorithms in [1]. In ALOHA-based algorithms, the reader broadcasts a frame length and each tag randomly picks one slot in the frame. If none or more than one tag picks the same slot, an empty or collision slot occurs. The tag can be identified only if it is the only one who picks one single slot. To approach the optimal throughput of ALOHA, dynamically adjusting the frame length according to the number of left tags is discussed in [7]. Zhang et al. [18] propose to decode the collided IDs by subtracting the known ones. The ALOHA algorithm defined in [1] uses RN16 to reduce the collision cost. In the selected slot, the tag transmits an RN16 first and transmits ID only after receiving the same feedback RN16 from the reader. However, the RN16 itself increases the overall overhead. Buettner and Wetherall [2] adjust the physical layer operating parameters, e.g., frequency, to enhance the tag read rate. A probabilistic model based on ALOHA protocol is proposed to enhance the RFID systems' performance in a mobile environment [4]. Sheng et al. [19] design a continuous scanning scheme to enhance the system throughput of mobile reader in large warehouse. The basic idea is utilizing the information of identified tags to reduce the scanning time of the following ones.

Tree-based algorithm works as follows: the reader constructs a binary tree according to the tag ID, e.g., "010101." In this binary tree, each node contains an ID prefix, e.g., "0" for the root, the prefix contained by the left child of one node plus a "0" bit and that of the right child plus a "1" bit. The children of the root contain "00" and "01." The leaves of this tree contain all possible IDs. Different algorithms [8], [9], [10], [11], [12] are proposed to enhance the efficiency of tree traverse. To make up the deficiency of tree-based algorithms on tag ID distribution, a smart trend traverse (STT) protocol [8] is proposed to tolerate different ID distributions. In some monitoring tasks, the tags need to be identified many times, and the known tags can be identified more efficiently [9] by tree-based algorithms. The EPC protocol [1] defines a "Select" command, which can be used to select a group of tags with the same ID prefix. The tree-based algorithms are known to be sensitive to the height of the tree and tag ID distribution.

2.2 CSMA in Networks

CSMA is a probabilistic MAC protocol, in which a node verifies the absence of other transmissions before transmitting on a shared medium. CSMA/CD is used to improve CSMA performance by terminating transmission as soon as a collision is detected [16] in wired networks. In wireless networks, the node is not able to sense when transmitting, CSMA/CA (collision avoidance) [13], [14] is used to reduce the probability of collision in wireless networks. A recent work [15] proposed a CSMA/CN (collision notification) method, which uses signal signature to notify the sender that a collision occurs at the wireless receiver side, so that the sender can abort the transmission if collision occurs. All the work on CSMA assumes that the node is able to sense the channel or identify special signature when transmitting, which is not practical for passive tag in RFID systems. RCSMA adopts a different approach, where the reader broadcasts the channel condition and the tags "sense" the reader's transmission instead of other tags'.

3 RCSMA Design

In this section, we discuss the detailed design of RCSMA and present its features where it can enhance the tag

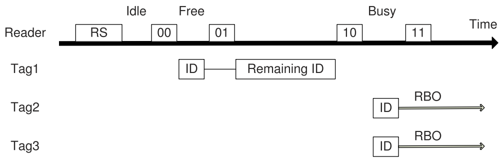

Fig. 1. RCSMA. The Reader broadcasts a Request Start command to start a tag identification task. In this task, the reader sends REQ command (four kinds of REQ,"00," "01," "10," and "11") to tell the channel condition (Idle, Busy, or Free) and divide time into slots. Each tag changes the contention probability in each slot. One tag will conduct Random BackOff (RBO) if collision occurs or transmit the remaining ID if the channel is free for transmission.

identification efficiency in RFID systems. One challenge to achieve CSMA in RFID is the limited capability of passive RFID tag, which is incapable of low SNR carrier sense [1]. One tag cannot sense the transmission of another even the two tags are very close. The unique feature of RCSMA in RFID systems is that the tags sense and decode the reader's transmission instead of other tags'. To achieve this, the reader needs to broadcast the channel conditions to the tags in every slot, based on which, the tags can update the contention probability in every slot. When the tag decides to contend, it transmits a prefix of ID instead of the whole ID or an RN16, which reduces the cost of collision and RN16 transmission. The tag transmits the remaining ID if the channel is free for its transmission. An illustrative example of RCSMA can be found in Fig. 1.

The benefits of RCSMA come from its low coordination cost and collision cost on tag identification cost. Coordination cost means the time cost on reader transmission and collision cost refers to the time cost on tags' collisions. Toward the RCSMA tag design, the tag needs the capabilities on maintaining states and switching contention probability according to reader's commands, which are already defined in the C1G2 UHF RFID protocol [1]. Therefore, we believe RCSMA does not need special hardware RFID tag design.

3.1 Channel Condition Broadcasting

The basic idea of CSMA protocols is that the single node is able to know the channel conditions and acts according to it, e.g., back off if there is a transmission, but that is not the case in UHF RFID systems. The tag is too simple to be able to sense the channel conditions by itself. In RCSMA, the reader broadcasts the channel conditions to the tags, based on which the tags have the capability of "carrier sense." In RCSMA, the reader only transmits the channel conditions after starting one identification task. This design brings two benefits. First, it reduces the reader's transmission cost on starting query rounds (such as framed ALOHA [1]), because it has only one round. Second, it reduces the reader's transmission cost on tag population selection (such as binary tree algorithm [8]).

In this design, the reader broadcasts a Request Start (RS) command to start one tag identification task. In one tag identification task, the reader broadcasts this command only once. This command defines the tag's modulation type, the uplink/downlink transmission data rate and the initial contention probability, and so on. The reader also records the current contention probability as system state information. Afterward, the reader broadcasts Request (REQ) command to divide the time into slots and inform the tags the channel condition in each slot.

There are three kinds of channel conditions:

- Idle. The reader does not detect any transmission.
- Busy. The reader detects a high energy but fails to find the header.
- Free. The reader decodes a header from the transmission.

To represent these three conditions, we need a 2-bit field at least in REQ. Besides, the transmission of tag ID is a two-stage process. The tag transmits a prefix of ID first, and then transmits the complete ID if the condition is indicated as *free* for transmission. The reader is required to tell the tag if the ID is successfully and completely received. Hence, we need another channel condition for that. There are four kinds of REQ commands to indicate the channel conditions:

- REQ("00"). If nothing is received.
- REQ("11"). If collision occurs.
- REQ("01"). If the header of one tag is detected.
- REQ("10"). If one tag's ID is successfully and completely received.

3.2 Contention Probability Update

One feature of our passive RFID tag is that each tag maintains its contention probability on its own. The tag checks to transmit in each slot. The advantage of this design is that the contention probability fast converges to optimum. The contention probability is updated in every slot instead of in each long round in traditional ALOHA protocol [1]. We will show that RCSMA can reduce the cost on approaching the optimal contention probability comparing with traditional tag number estimation schemes, e.g., the ALOHA-based scheme needs many rounds to estimate the number of tags [3], [6].

The tag stores a *contention window* d_w to represent its contention probability. In each time slot, the tag randomly picks one number in the interval $[0, d_w - 1]$ as the *slot number* d_s, and the tag transmits its ID only when its *slot number* is equal to zero. In one slot, if one tag decides to transmit ($d_s = 0$), it transmits a prefix of ID first. If the reader sends another command to indicate that the prefix is successfully received, the tag transmits the rest of ID. We will discuss this design in the next section.

The contention window of all the tags is updated according to the following rules:

- If the channel is notified as "busy," all tags double the *contention window* size.
- If the channel is notified as "idle," all tags halve the *contention window* size.
- If the channel is notified as "free" or the reader indicates a complete ID transmission, all tags keep the *contention window* size unchanged.

3.3 Transmission and Collision Cost Minimization

In tag identification tasks, the tag usually transmits its ID directly [8], [9], [12], [18] and the collision cost is very high. The EPC protocol adopts an RN16 contention scheme to reduce the collision cost [1], but the RN16 itself brings high

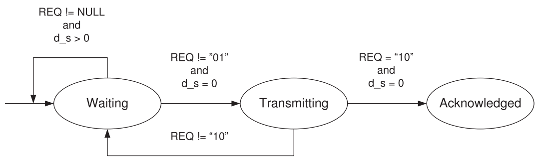

Fig. 2. The states of the tag.

cost on both the reader's and the tag's transmissions. In RCSMA, if one tag chooses to transmit, it transmits an ID prefix and waits for the next command, if the next command indicates that the channel is "free," it transmits the remaining ID, if not, the tag contends for transmission again. This design reduces the collision cost, as the collision of the ID prefix is much less than that of the whole ID. Meanwhile, it reduces the transmission cost of RN16 by the tags and the feedback RN16 by the reader [1].

To control transmitting the ID prefix or the remaining ID, each tag maintains a state and updates it once an REQ command is received. As shown in Fig. 2, there are three states in RCSMA, Waiting, Transmitting, and Acknowledged. The tag starts with a "waiting" state and switches to "transmitting" state after transmitting its ID prefix. If the ID is completely received by the reader, the tag switches to "acknowledged" state after receiving the REQ("10") command. Otherwise, the state will be turned back to the "waiting" state.

After the tag is turned into the "acknowledged" state, it may choose to keep silent or return to "waiting" state. This functionality is defined in the RS command by the reader. If the acknowledged tags keep silent, the remaining tags can be more efficiently identified [19]. In some cases [22], [23], [25], the reader may choose to monitor the tags by collecting their IDs repeatedly. Therefore, the tag may return to "waiting" state.

4 Theoretical Analysis

In this section, we build an absorbing Markov chain model to analyze the efficiency of RCSMA on tag identification tasks. The absorption means the system terminates after all the tags are identified, by which we can get the throughput of the system (number of identified tags over the absorption time (AT)).

4.1 Markov Chain Model

We build an absorbing Markov chain for our system in this section. The input of our model is the number of tags N and the maximum contention window size W. The contention window is used to record the system contention probability, e.g., the minimum contention probability is $1/W$. The output of our model can be the throughput of one tag identification task. Based on previous assumptions, the state of the system can be described by a two-dimensional vector $s = (x, d_w)$, where x is the number of unidentified tags and d_w is the contention window size. At the start of system, the number of unidentified tags is $x = N$. We do not specify an initial window size here as the performance of RCSMA is insensitive to the initial contention window size (we will show in Section 5). We describe the dynamic behavior of the system as a Markov chain (we will prove its absorption later). Let $P = [p_{ss'}]$ be the corresponding

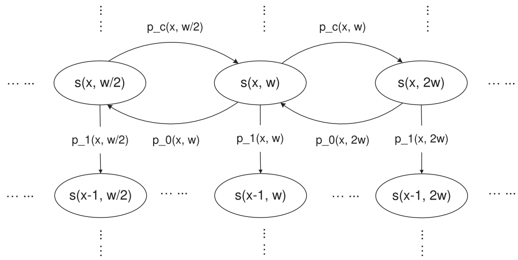

Fig. 3. State transitions of transient states in the Markov chain, where w is the contention window size. The number of tags, x, is decreased by 1 to identify each tag.

transition matrix, $p_{ss'}$ or p_{ij} is the transition probability from the state s or state i at the start of one slot to the state s' or state j at the end of one slot. Let N be the number of tags and W is the maximum contention window size, so the transition matrix A is considered to have $n \times n$ elements, where $n = (N + 1)(log_2 W + 1)$.

The analysis of this Markov chain is the study of its transient behavior. The quantities needed are the following:

1. The probability of a successful transmission during a slot, when the state of the system is $s = (x, d_w)$:

$$p_1(x, d_w) = \frac{x}{d_w}\left(1 - \frac{1}{d_w}\right)^{x-1}. \tag{1}$$

2. The probability that no tag transmits during a slot, when the state of the system is $s = (x, d_w)$:

$$p_0(x, d_w) = \left(1 - \frac{1}{d_w}\right)^{x}. \tag{2}$$

3. The probability of collision during a slot, when the state of the system is $s = (x, d_w)$:

$$p_c(x, d_w) = 1 - p_1(x, d_w) - p_0(x, d_w). \tag{3}$$

The elements of the matrix P, e.g., $p_{ss'}$, can be computed from $p_0(x, d_w)$, $p_c(x, d_w)$, and $p_1(x, d_w)$ as follows:

$$\begin{cases} p_0(x, d_w) & d'_w = max(0, \lceil d_w/2 \rceil). \\ p_c(x, d_w) & d'_w = min(W, d_w * 2). \\ p_1(x, d_w) & x' = x - 1. \end{cases} \tag{4}$$

The corresponding state transition can be found in Fig. 3, where the chain is in an iterative and layered structure. Note that in all the previous formulas, and the formulas that will follow, P is considered to be $n \times n$ matrix, where $n = (N + 1)(log_2 W + 1)$. That is, the vector H_i has been mapped into a scalar according to the following transformation:

$$\begin{aligned} H_i = x * (log_2 W + 1) + d_w \; for \; s(x, d_w), \\ x = 0, 1, \ldots, N, d_w = 1, 2, \ldots, log_2 W + 1. \end{aligned} \tag{5}$$

Another property of this Markov chain is absorption, which means all the states go to one or several states eventually, and we prove it as below.

Theorem 1. *The Markov chain constructed by the transition matrix P (see Fig. 3) is an absorbing Markov chain [24].*

Proof. Can be found in supplemental file, which can be found on the Computer Society Digital Library at http://doi.ieeecomputersociety.org/10.1109/TPDS.2011.240. □

This meets the fact that the identified tags will leave the system and the system will terminate when all the tags have been identified.

5 Evaluation

Our evaluation consists of two parts. The first part is the evaluation on RCSMA, where we evaluate the convergence of RCSMA and compare the experimental results with theoretical results. The second part is the experimental comparisons, where we compare RCSMA with optimized ALOHA schemes and optimized tree schemes under different scenarios.

In our system, the number of tags N is varied from 1 to 1,024. Correspondingly, the contention window size of one tag ranges from 1 to 1,024. The commercial tags have as large as 2^{15} possible slot selections [1], as the minimal memory bank size of tag is 16 bit. We use 2^{10} as it is large enough for our analysis and evaluation. The data rate of tag ranges from 16 to 64 kbits/s and that of reader ranges from 2 to 32 kbits/s. The tag data rate is generally larger than reader data rate as the decoding capability of tag is limited by its simple design, e.g., the maximum data rate of tag is 640 kbits/s and that of reader is 128 kbits/s [1].

The simulator is implemented in C++. In the simulator, the system time is divided into slots. In each slot, the reader sends a command to the tags and the tag responds with corresponding message [26]. Each kind of readers and tags has been designed as a class. The results are collected in each reader tag pair simulation.

5.1 Compared Schemes

To grindingly test the performance of RCSMA, we give the best parameter settings on ALOHA-based and tree-based algorithms.

5.1.1 ALOHA-Based

The optimal performance of ALOHA can be achieved by setting the frame length to be equal to the number of tags in each round. We assume that the ALOHA reader magically knows the number of tags already. Notice that the number of tags needs to be estimated in reality [3], [6], [19]. In our evaluation, we ignore the cost on tag number estimation to see the maximum tag read rate the ALOHA scheme can achieve.

Optimal EPC ALOHA (OEA). The detail settings can be found in [1], where the framed ALOHA adopts an RN16 scheme to reduce the collision cost, in which the tag transmits RN16 to contend for identification before sending the ID.

Optimal framed ALOHA (OFA). The reader broadcasts a frame length and each tag randomly picks one slot to transmit ID. The difference to OEA is that the tag transmits the ID directly in picked slot, such as in [7], [18]. The rest settings are the same as OEA.

5.1.2 Tree-Based

The tree-based algorithm is known to be sensitive to the tree height and ID distribution. The height is a fixed value (96 bits) for off the shelf RFID tags [1]. To show the best performance of tree-based algorithms, the IDs are uniformly distributed in our simulation.

Optimal EPC binary tree (OEBT). The EPC C1G2 UHF RFID protocol [1] uses a hybrid design, that is, the reader broadcasts a "select" command to choose a group of tags with same ID prefix and uses an ALOHA round to identify these tags (the tree algorithm can be implemented by setting the frame length to 1).

Optimal binary tree (OBT). The algorithm details are the same as STT in [8]. Further, we use a tree only algorithm, where the ALOHA process and extra bit field in "select" command are removed. In OBT, the reader broadcasts an ID prefix and the tag responds to its ID directly if it is a matched ID prefix.

5.2 Metrics

Absorption time. It refers to the absorption time of the Markov chain, or the time to identify a set of tags. Toward the evaluations on this metric, each tag is identified only once.

Tag read rate. It refers to the number of identified tags in the given time interval, e.g., 1 second. It is an essential metric for RFID systems [1]. Each tag may be identified many times to get an average tag read rate.

Bits per tag (BET). It refers to the average number of bits transmitted by the tag or reader to identify each tag. BET consists of bits of reader per tag and bits of tag per tag, which means the average number of bits transmitted by the reader and tag, respectively. This metric is used to understand the coordination cost on reader and tag.

Channel utilization. It refers to the percentage of time that is used for tag ID transmission only. This metric may help us on understanding the bottleneck of tag identification performance and revealing further improvement possibilities on traditional identification algorithms and new designed algorithms.

5.3 Summary of Results

Our analysis and experiments reveal the following findings:

- Best ALOHA is better than best tree. The best ALOHA-based scheme is OEA [1]. It is better than the best tree-based scheme, which is OBT [8]. We compare the optimized algorithms only as they are difficult to be fairly compared due to the different parameter settings.
- RCSMA is able to fast converge. The contention probability of RCSMA can converge to optimum in $O(logn)$ time, where n is the maximum contention window size.
- RCSMA improves the tag read rate by 30-70 percent when comparing with the best ALOHA-based algorithm, which is OEA, under different reader and tag data rates.
- The tag identification scheme is sensitive to the reader data rate. Particularly, the performance of tree-based algorithms is extremely poor in low reader data rates.
- The channel utilization of RCSMA is only 40 percent when tag data rate is four times of reader data rate, which indicates that further improvement is possible.

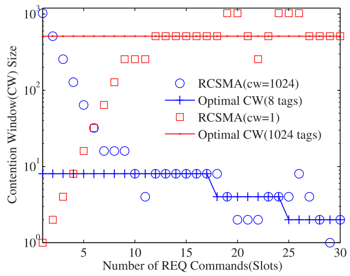

Fig. 4. Convergence. The number of slots that the RCSMA needs to converge to optimal contention probability.

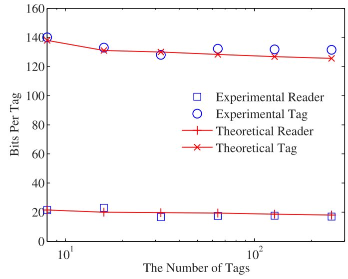

Fig. 6. Bits per tag. The comparison between the experimental bits per tag and theoretical bits per tag.

5.4 Evaluation on RCSMA

In this section, we want to understand the convergence of RCSMA as well as the accuracy of our simulation and Markov chain model.

We test the convergence of RCSMA by two cases in Fig. 4. First, there are eight tags in the field and the initial contention window size of RCSMA is 1,024. Second, there are 1,024 tags and the initial contention window size of RCSMA is 1. Both cases show that the RCSMA can reach to optimal contention window size in $logn$ steps, where n is the difference between the current contention window size and the optimal contention window size. Traditionally, the optimal frame size needs to be estimated by many rounds [6] in ALOHA-based schemes, but RCSMA needs only few slots to approach to optimum.

In Fig. 5, we compare the absorption time of the Markov chain model with the tag identification finish time in the simulation. The absorption time of the Markov chain is calculated by the model built in previous section. The identified tags will keep silence in this evaluation. The tag identification finish time is the time that all the tags have delivered their IDs to the reader. In this comparison, the number of tags ranges from 8 to 256 and the maximum contention window size is 512, which are restricted by the large matrix calculation capability of MATLAB and the calculation of larger matrix size will be aborted. The differences between the theoretical absorption time and experimental results are caused by the matrix size. The state transition may traverse all the possible states, e.g., when the contention window size is 1,024. However, the size of matrix we use cannot contain all the states. Thus, the calculation of number of state transition steps is less than actual number. The theoretical absorption time is less than the task finish time.

We compare the number of transmitted bits per tag between the model and the experimental results in Fig. 6. The bits per tag helps us understanding the accuracy of our model and the performance of RCSMA in the perspective of uplink/downlink (tag to reader/reader to tag) data rate difference. The number of bits transmitted by the reader is decided by the number of REQ commands. The bits transmitted by the tag consist of the ID bits and the header bits. As shown in Fig. 6, the theoretical result fits the experimental results very well.

5.5 Comparison with Different Schemes

We compare RCSMA with four well chosen schemes: optimal EPC ALOHA, optimal framed ALOHA, optimal EPC binary tree, and optimal binary tree. We call them "optimal" as we set the best parameters setting for them. We assume the ALOHA-based schemes always know the number of unidentified tags so that it can adjust to the optimal frame length. Note that there is no ALOHA-based algorithm that is able to exceed the performance in our simulation as the number of tags is difficult to get in reality. Similarly, we assume the tags' IDs are uniformly distributed. Thus, the tree-based algorithm can reach the best performance. The tree-based algorithms use the algorithm designed in [8], which is the best tree-based algorithm we can find.

5.5.1 *Tag Read Rate*

The number of tags varies from 1 to 1,024, which is a favorite setting for both ALOHA-based scheme and RCSMA. The tag we used here keeps contending for transmitting its ID even it is already identified. We use identical data rate for the reader and tag (16 kbits/s) here. As shown in Fig. 7, the RCSMA can generally outperform the best of the rest four schemes by 30 percent. The tag read rate of RCSMA is very high when tag number is small, e.g., only one tag. Since there is no collision happened, the RCSMA can use the optimal contention window size (one) to repeatedly identify this tag.

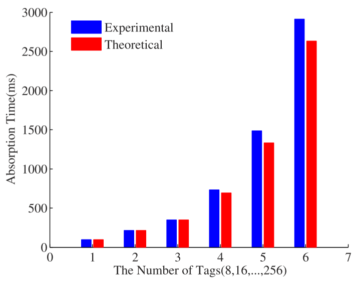

Fig. 5. Absorption time. The comparison between experimental results and theoretical results.

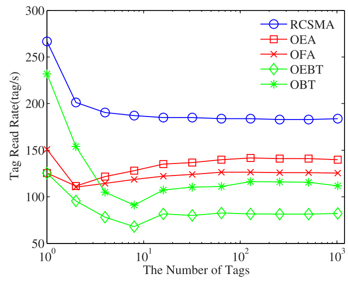

Fig. 7. Tag read rate. It is measured by the number of tags that can be identified per second.

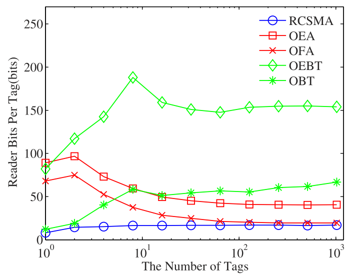

Fig. 8. Reader bits per tag. It is measured by the number of bits transmitted by the reader to identify each tag.

Toward ALOHA-based algorithms, OFA is a little better than OEA as there is no extra cost on the tag ID transmission of OFA. In OFA, the tag transmits its ID directly in the selected slot. And the EPC tag transmits an RN16 to contend for identification in the picked slot [1]. When there is only one tag, OEA causes extra cost on the RN16 transmission. With the increase of tag number, the OEA can generally outperform OFA as the RN16 scheme reduces the collision cost.

Toward tree-based algorithms, both have relative good performance when tag number is in a small scale, as the ID prefix of reader does not need to traverse deep for small number of tags. The OEBT and OEA have the same performance when there is only one tag as their settings are the same if there is only one tag [1]. OEBT uses an extra ALOHA process (the frame length is always 1) to identify the tags. The OBT is generally better than OEBT due to the extra cost on each selection in OEBT, even there is RN16 scheme in OEBT to reduce the collision cost.

5.5.2 *Bits per Tag*

This test consists of two parts, the reader bits per tag part and tag bits per tag part. We want to see the coordination cost on reader and tag, respectively.

As shown in Fig. 8, the reader bits per tag is measured by the number of bits transmitted by the reader over the number of identified tags (each tag may be identified many times). RCSMA broadcasts the channel condition only, so the reader cost is very small. In ALOHA-based algorithms, OFA has similar reader bits per tag to RCSMA, as it needs QREP command only to move to next slot. OEA has a little more bits per tag due to extra RN16 cost in the ACK scheme of EPC ALOHA [1]. Toward tree-based algorithms, the reader needs to broadcast more bits (the extra ID prefix for each selection). OEBT uses the most number of bits as it needs an extra ALOHA process and the RN16 scheme.

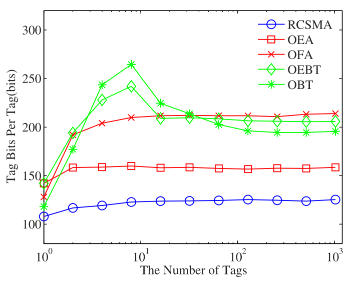

Fig. 9. Tag bits per tag. It is measured by the number of bits transmitted by the tag to identify each tag.

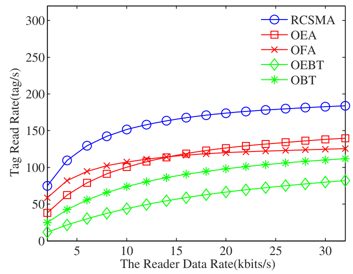

Fig. 10. The tag read rate versus reader data rate.

The tag bits per tag are compared in Fig. 9. The tag transmission of RCSMA consists of the delivery of ID with header only, so the number of bits transmitted by each tag is comparably smaller than that of other schemes. Again, the OFA needs more bits than OEA as the cost of ID collision. The tree-based algorithms, OBET and OBT, have the similar tag bits per tag.

5.5.3 *Different Data Rate*

We compare RCSMA with other schemes under different uplink/downlink data rate settings. The different data rate of reader and tag is another perspective for new identification algorithm design because tag identification algorithms may be highly sensitive to the reader data rate. The tag data rate is generally larger than reader data rate [1]. Thus, the data rate of reader in our test ranges from 2 to 32 kbits/s and that of tag ranges from 16 to 64 kbits/s. We conduct this experiment by 1,024 tags.

Under different reader data rates, RCSMA reveals outstanding performance among all the schemes in Fig. 10. Interestingly, the tag read rate of OFA is better than that of OEA in small reader data rates, e.g., less than 15 kbits/s. In OEA, the reader needs to transmit an ACK for each received RN16, the ACK scheme brings more coordination cost on reader transmission. In lower reader data rates, the OFA performs very well. Tree-based algorithms are highly sensitive to the reader data rate as the reader needs to broadcast ID prefix to identify the tags. The best tree-based algorithm can only reach half of the tag read rate of best ALOHA-based algorithm in lower reader data rates.

Under different tag data rates, not surprisingly, the performance of RCSMA (as well as other schemes) increases as the tag data rate increases, which are shown in Fig. 11. The tag read rate of RCSMA increases faster than other schemes as the tag data rate increases. The reason is that the tag bits transmission in RCSMA occupies a high percentage in the overall transmission.

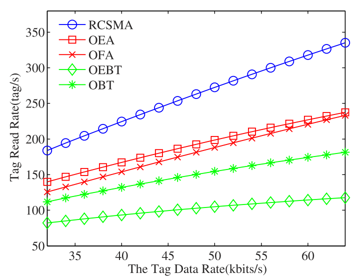

Fig. 11. The tag read rate versus tag data rate.

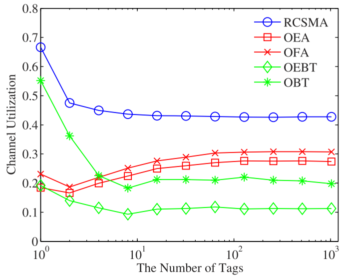

Fig. 12. Channel utilization.

5.5.4 Channel Utilization

We further test the channel utilization of tag identification schemes in RFID systems. The channel utilization is measured by the time used for the ID transmission over the time for the overall identification process. This helps us to preview the possible improvement on tag identification schemes. There are two data rates in this test, 8 kbits/s for the reader and 32 kbits/s for the tag. As we can see in Fig. 12, the channel utilization of RCSMA can only reach 40 percent and other schemes are even lower, e.g., 30 percent for ALOHA-based algorithms, 10 and 20 percent for tree-based algorithms. Besides the poor design of tree algorithm in EPC protocol [1], it is possible for further improvement on the tag identification algorithms, including RCSMA.

6 Conclusion and Future Work

In this paper, we propose a new tag identification scheme called RCSMA in UHF RFID systems. In RCSMA, the reader broadcasts the channel condition in each time slot and the tags "sense" the channel information from the reader. Meanwhile, each tag adjusts its contention window according to the channel condition in each slot. Compared with ALOHA-based and tree-based tag identification algorithms, RCSMA has the following advantages: first, it has little coordination cost. Second, it is insensitive to the number of tags and the tags fast converge to optimal contention probability. Third, it is independent on the tag ID distributions. According to theoretical analysis and extensive simulation, the RCSMA can achieve 30-70 percent improvement on tag read rate comparing with the best ALOHA algorithm. For the future work, we may investigate tag number estimation algorithm based on RCSMA.

Acknowledgments

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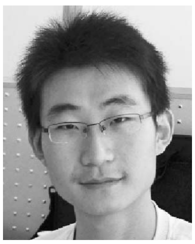

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