A collision-tolerant based anti-collision algorithm for large scale RFID system

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***Abstract*—Tag identification is an important issue in RFID system. Most existing anti-collision algorithms solely focus on reducing collision probability while suffering from vast idle slots. This paper proposes a collision-tolerant dynamic framed slotted Aloha (CE-DFSA) algorithm which attempts to identify multiple tags in a slot to reduce the total identification time in the process of identification. In CE-DFSA, tags are allocated with orthogonal Walsh Sequence (WS) so that multiple tags can be identified in a time slot without spreading the spectrum. Simulation results show that the proposed algorithm considerably accelerates the tag identification process with improved efficiency compared with existing anti-collision algorithms.**

***Index Terms*—RFID, anti-collision, orthogonal, WS.**

I. Introduction

RADIO frequency identification (RFID) is widely used for automatic identification as a replacement of the barcodes because of its more feasible, convenient, speedy, and contactless features. A typical RFID system is composed of a reader and multiple tags [1]. Each tag has a unique identifier (UID) or electronic product code (EPC) (collectively called ID hereinafter), and the reader identifies all tags through a shared wireless communication channel [2]. When multiple tags transmit their IDs simultaneously, collision may happen in which case none of tags can be identified by the reader and system efficiency will be negatively affected particularly in a large scale system. To cope with the collision problem, various anti-collision algorithms have been proposed, which can be classified into two categories: deterministic [3] and probabilistic [4] algorithms.

Deterministic algorithms resolve a collision by splitting collided tags into disjoint subsets iteratively until all tags are identified. Such methods incur relatively long identification latency, especially when the number of tags is large. Probabilistic algorithms [5-6], however, reduce the probability of collision by dividing the time into slots and sequentially identifying the tags in separate time slots. Aloha-based algorithms are the most prevalent probabilistic solution used in the ultra high frequency (UHF) RFID systems due to its simplicity in implementation. Particularly, the dynamic framed slotted Aloha (DFSA) algorithms are the most popular ones [7-8].

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Limited by the computational ability of a reader, DFSA algorithms [5-6] with high computation overhead are inefficient in terms of computation cost. To enhance the performance and reduce the complexity of DFSA, latest energy efficient algorithms have been developed [7-8]. The literature [7] proposed an Improved Linearized Combinatorial Model (ILCM) that only incurs a modest calculation cost, and can be easily implemented as a tag backlog estimation method. Nonetheless, its performance deteriorates when the number of tags varies in a large scale. The authors in [8] presented an effective frame breaking policy named detected sector based dynamic framed slotted Aloha (ds-DFSA) which can improve the system throughput up to 0.41. However, an extra stack is required to record the indexes of collided slots, and individual identification for each collided slot is difficult to proceeded.

Recently, the work on spatial collision recovery (SCR) on top of the framed slotted Aloha (FSA) was presented in [9], where a post-preamble for channel estimation was introduced upon the modified UHF RFID standard. The SCR can recover from up to eight collisions in a slot by utilizing four receive antennas at the reader. To be better compatible with the EPCglobal C1 Gen2, an advanced strategy based on the post-preamble is proposed in [10]. However, both solutions need to be implemented in a multi-input multi-output (MIMO) readers receiver by adding the eight bits post-preamble and thus bring the extra cost for both reader and tags.

To further improve the identification performance of DFSA while keeping the computation overhead at a low level, in this paper, we propose a collision-tolerant dynamic framed slotted Aloha (CE-DFSA) algorithm that tries to identify multiple tags in a slot to reduce the total identification time in the process of identification. Particularly, when the reader issues a query, multiple tags within a slot that have mutually orthogonal Walsh Sequence (WS) respond, in such a way that WSs can be separated by the reader without spreading the spectrum. The simulation results are supplemented to show that the proposed scheme outperforms current anti-collision algorithms in terms of system throughput, time efficiency and average coordination time for one tag identification. Moreover, the proposed solution can be easily implemented in the conventional reader with single antenna.

II. The Proposed CE-DFSA Algorithm

In CE-DFSA algorithm, instead of transmitting a RN16 in a traditional DFSA algorithm, a tag transmits a 16-bits signal denoted as WS representing a signature sequence randomly selected from a memory bank. Specifically, the WS signal occupies time and bandwidth as same as that of RN16 signal. The WS signal can be achieved by non-return-to-zero encoding at the chip rate which is the same as the bit rate. Once the reader identifies the WSs of the responding tags, the reader is able to identify multiple tags. The wireless channels between the reader and tags are described by a vector $\mathbf{h} = [h_1, ...h_i, ...h_N] \in V_{1\times N}$. Considering the relatively static application scenario, a block fading channel is assumed between each tag and the reader and the channel gain h_i is constant during the identification process. The tags are assumed to be synchronized when they respond to the reader. It is noted that in the case of non-synchronization, the frequency tolerance can be restrained by adjusting clock frequency dynamically according to backscatter link frequency (BLF) required by the reader. The proof of this approach is provided in [11]. We use $\mathbf{X}$ to denote the WSs. Assuming that the WS length of each tag responding to the reader is L bits, the composite signal received by the reader from N tags is

$$\mathbf{y} = \mathbf{h}\mathbf{X} + \mathbf{n} \tag{1}$$

herein $\mathbf{n}$ is the additive white noise at the reader's receiver, $\mathbf{y} = [y_1, ...y_i, ..., y_L] \in V_{1\times L}$, where y_i represents the i-th bit of the composite signal received by the reader. $\mathbf{X} = [\mathbf{x}_1, ...\mathbf{x}_i, ...\mathbf{x}_N] \in V_{N\times L}$, where $x_{i,\ j} \in \{-1,\ +1\}$ represents the j-th bit of the signal transmitted by the i-th tag. In order to simplify the analysis, the input noise is not considered in the following discussions.

We assume N tags responding to the reader with their WSs within the operation range. $\mathbf{x}_i$ (i is an integer) denotes one tag's WS. Note that all of N WSs are orthogonal, i.e.,

$$\mathbf{x}_i \cdot \mathbf{x}_j = 0,\ i \neq j,\ (i,\ j \in 1,\ 2, ...,\ N) \tag{2}$$

The reader can decode the corresponding signals and collect the channel information utilizing the orthogonality. According to the received information from tags, the reader can obtain

$$h_{i\ (i\in 1,\ 2,...,\ N)} = \frac{\mathbf{y}\cdot\mathbf{x}_i}{L}\begin{cases} > 0,\ if\ \mathbf{x}_i\ is\ transmitted \\ = 0,\ otherwise \end{cases} \tag{3}$$

According to expression (3), the reader can decode the corresponding WSs and obtain the channel information $\mathbf{h}$, which can be further used as needed, e.g., to give a coarse estimation of the received signal strength index (RSSI), which is outside of the scope of this work. It is noted that although the multiple WSs detection method shown in (2) and (3) is similar to that employed by CDMA-based RFID systems, our solution is distinct because each WS itself serves as an orthogonal code relative to other WSs sent in the same slot and the transmit signal spectrum is not spread out. Fig. 1 gives an identification example of our proposed CE-DFSA algorithm. As can be observed, the proposed CE-DFSA algorithm consumes only one time slot to identify two tags. Compared to the traditional DFSA algorithm, the system throughput has been improved and the total time has been reduced. Hence, the CE-DFSA can enhance the identification performance of the RFID system.

To simplify the setup of the proposed method, we design a set of mutually orthogonal WSs with 16-bits by utilizing Hadamard matrix. Formally, the tag WS space can be represented by a L-dimensional binary vector space $\{-1,\ +1\}^L$, where each tag WS (data 1 and 0 can be represented as +1, and -1, respectively) is a row vector in this space. Since each Hadamard matrix has L row vectors which have L elements, the whole vector space $\{-1,\ +1\}^L$ can be divided into $2^L/L$ disjoint subsets. In our proposed CE-DFSA, we only need to choose one subset as WS set. Considering an example with L=4, we use the 4-bit Walsh matrix as the WS set, i.e.,

$$W = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

herein each row or column representing one tag's WS. Assume tags 1 and 4 collided in a slot, whose WSs being 1111 and 1001, the reader received the following composite signal

$$\mathbf{y} = \mathbf{h}\mathbf{X} + \mathbf{n} = h_1\mathbf{x}_1 + h_4\mathbf{x}_4 \tag{5}$$

where $\mathbf{X} = \begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_4 \end{bmatrix} = \begin{bmatrix} +1 & +1 & +1 & +1 \\ +1 & -1 & -1 & +1 \end{bmatrix}$. The two rows of $\mathbf{X}$ are mutually orthogonal, i.e., the tags 1 and 4 send orthogonal WSs to the reader. The reader can identify two WSs and separate them by correlation, i.e.,

$$\mathbf{y}\cdot\mathbf{x}_1 = h_1 L,\ \mathbf{y}\cdot\mathbf{x}_2 = 0,\ \mathbf{y}\cdot\mathbf{x}_3 = 0,\ \mathbf{y}\cdot\mathbf{x}_4 = h_4 L \tag{6}$$

It is noted that the above process is similar to multiuser demodulation in a CDMA system. The difference is that no spectrum spreading is required in our method. For L=16, we can use the same method to obtain the required WS set for tags. In order to reduce the implementation complexity, we just pre-compute WS set and store them into the reader and tags during the manufacture. Each tag involved in a slot will select one of the set.

III. Performance Evaluation of The Proposed Algorithm

We consider that there are n tags in a RFID system, the frame size is F and the length of WS is k. To characterized the proposed scheme, the probability of successful, collision, and idle tag states needs to be calculated. Let P_e denote the probability that no tag selects a slot, we have:

$$P_e = C_n^0(1/F)^0(1-1/F)^n = (1-1/F)^n \tag{7}$$

In the next step, the probability of successful identification should be discussed. This probability is denoted by P_s which can be written as

$$P_s = P_s^{one} + P_s^{multi} \tag{8}$$

where P_s^{one} is the probability that only one tag selects the current slot, P_s^{multi} denotes the probability that multiple tags respond to the reader in a slot but with different WSs. Let $P_{r/k}$ denote the probability that r tags select different r WSs from k sequences. $P_{r/k}$ can be computed as:

$$P_{r/k} = \frac{k(k-1)...(k-r+1)}{k^r} \tag{9}$$

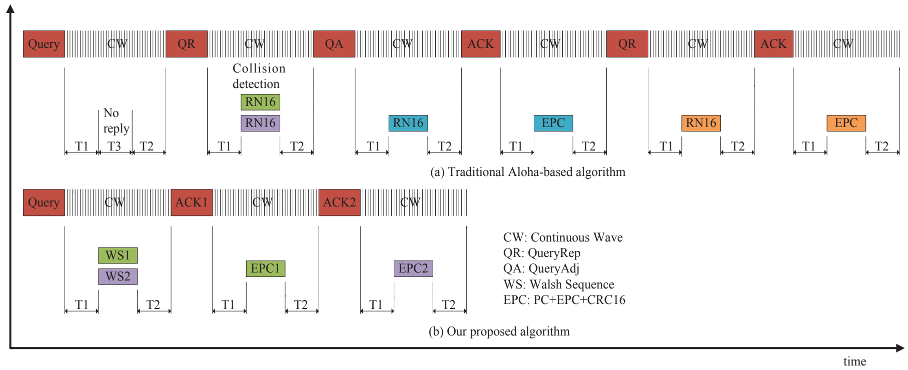

Fig. 1. An identification example of our proposed CE-DFSA

In order to formulate P_s^{multi}, we firstly need to compute the probability that multiple tags select a same slot. Let $P_{ms} = \sum_{r=2}^{n} C_n^r (1/F)^r (1-1/F)^{n-r}$. Eq. (8) can be rewritten as:

$$\begin{aligned} P_s &= C_n^1 (1/F)^1 (1-1/F)^{n-1} + P_{ms} \cdot P_{r/k} \\ &= \tfrac{n}{F}\left(1-\tfrac{1}{F}\right)^{n-1} + \tfrac{k(k-1)\ldots(k-r+1)}{k^r} \cdot P_{ms} \end{aligned} \quad (10)$$

Now, let P_c denotes the probability of collision in the proposed scheme, according to the analysis above, we have:

$$P_c = P_{ms} \cdot \left(1 - P_{r/k}\right) \quad (11)$$

We need to calculate the probability of the partial-collision state which is a part of the probability of collision because the reader always identifies a part of the tags in any partly-collided slot. $P_{full-col}$ denotes the probability of full collision which corresponds to the probability that all collided tags select the same WS ($P_{full-col}^1$) plus that of each active WS selected by at least two tags ($P_{full-col}^2$). The former is simple to compute:

$$P_{full-coll}^1 = P_{ms} / k^{r-1} \quad (12)$$

$$g_k\left(r,\ 2\right) = \sum_{i=0}^{r} (-1)^i C_r^i \cdot \frac{k!}{(k-i)!} \cdot g_{k-i}\left(r-i,\ 1\right) \quad (13)$$

where $g_k\left(r,\ 2\right)$ represents the number of ways in which r tags selecting k WSs with at least one conflict selection (more than one tag choose the same WS).

$$g_{k-i}\left(r-i, 1\right) = P\left(k-i,\ r-i\right) \cdot (r-i)^{k-i} \quad (14)$$

in which $P(k-i, r-i)$ is the probability that we have $(k-i)$ tags and $(r-i)$ slots and all the slots contain at least one tag. The mathematical expression for $P(k-i, r-i)$ is given by:

$$P\left(k-i,\ r-i\right) = \sum_{j=0}^{r-i} (-1)^j C_j^{r-i} \left(1 - \frac{j}{r-i}\right)^{k-i} \quad (15)$$

According to (13), (14), and (15), $P_{full-coll}^2$ is written as:

$$\begin{aligned} P_{full-coll}^2 = &\sum_{i=0}^{r} \sum_{j=0}^{r-i} (-1)^{i+j} C_r^i \cdot C_{r-i}^j \\ &\cdot \left[k!/\left(k-i\right)!\right] \cdot (r-i-j)^{k-i} \cdot P_{ms} \end{aligned} \quad (16)$$

The probability of full collision and part-collision are:

$$P_{full-col} = P_{full-coll}^1 + P_{full-coll}^2 \quad (17)$$

$$P_{part-col} = P_c - P_{full-col} \quad (18)$$

In a traditional DFSA algorithm, an appropriate frame size is required to avoid the collision as much as possible. Since the collided tags can be resolved by WSs, the performance and robustness can be enhanced by CE-DFSA under the same condition. From analysis of [8], we know that the tag backlog estimation error has a slight affect on system throughput. Therefore, we can use $n_{est} = 2.39 N_{ack}$ to estimate the tag backlog and adjust the frame size at the end of each identification round, where N_{ack} is the number of Ack command transmitted in collision slots during an identification round. After the tag backlog is estimated, the frame size can be set as $F = F_{opt}/2^m$ (m is an integer) to reduce the number of slots, where F_{opt} denotes the optimal frame size fitting the n_{est} in the traditional DFSA. Since excessive Ack commands in a collision slot may cause a time efficiency degradation of CE-DFSA, the value of m should be selected properly. Besides, considering the disparity between slot durations, the system throughput may not be effective to evaluate the performance of anti-collision algorithm in terms of identification time. So, in this paper we evaluate the algorithm in terms of the time efficiency, which can be defined by [3]:

$$\eta_{time\_effi} = \frac{n \cdot T_{ID}}{I \cdot T_I + S \cdot T_S + C \cdot T_C} \quad (19)$$

where I, S, and C represent the numbers of idle slots, successful slots and collision slots for the identification process; T_I, T_S, and T_C denote the corresponding time duration. T_{ID} is the time duration for transmitting tag ID. The parameters, i.e. I, S, and C in eq. (19) are counted by the reader during the identification process.

IV. Simulation Results

We evaluate the time efficiency and average coordination time to identify one tag of the proposed algorithm, and compare its performance with existing methods including Q-algorithm, MAP [4], ILCM [7], ds-DFSA [8], smart collision recovery (SCR) [9], backwards compatible improvement (BCI) [10], and DPPS [3] over extensive Monte Carlo simulations.

Note that the total time for identifying all tags consists of the necessary time for valid data (such as ID) transmission and coordination time such as the time duration of commands, guard

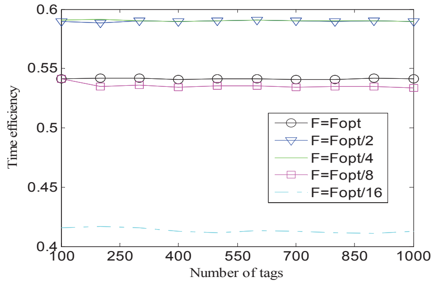

Fig. 2. Comparison of time efficiency for different F under the perfect condition

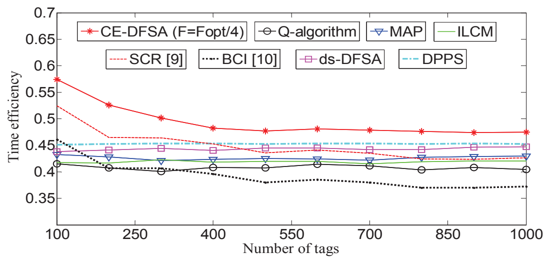

Fig. 3. Simulation results: time efficiency for various algorithms

time, i.e. T1, T2, T3, etc. To obtain the total and coordination time required to identify all tags, the time intervals of each slot type and commands used in the identification process should be measured. According to the EPCglobal C1 Gen2 standard specification, the primary time parameters are listed in Tab. I.

Fig. 2 presents the time efficiency of CE-DFSA for different F ($F = F_{opt}/2^m$, m=0, 1, 2, 3, 4) under the perfect condition (the number of tags is known for the reader). It is observed that the proposed method strike the best average performance under $F = F_{opt}/4$.

Fig. 3 compares the time efficiency for various algorithms with initial frame size F=16. As can be observed, the time efficiency of CE-DFSA is always better than that of other methods. The average time efficiency of CE-DFSA is about 0.4945, whereas the average time efficiency of BCI [10], Q-algorithm, ILCM, MAP, ds-DFSA, SCR [9], and DPPS is 0.3928, 0.4081, 0.4188, 0.4263, 0.4431, 0.4493, and 0.4529, respectively.

TABLE I
THE SIMULATION PARAMETERS ACCORDING TO EPCGLOBAL C1 GEN2

Parameters	value	Parameters	value
Reader-to-tag data-0	1Tari	RTcal	75µs
Reader-to-tag data-1	2Tari	TRcal	200µs
Reader-to-tag rate	40kbps	T1	250µs
Tag-to-reader rate	40kbps	T2	250µs
Tpri	25µs	T3	100µs
Tari	25µs	RN16	16bits
DR	8	EPC	96bits
Query	22bits	Ack	18bits
QueryAdj	9bits	QueryRep	4bits

Fig. 4 shows the simulation results of average coordination time required to identify one tag. As can be found, the proposed CE-DFSA algorithm spends average 2.8821 millisecond (ms) coordination time to identify one tag, whereas BCI [10],

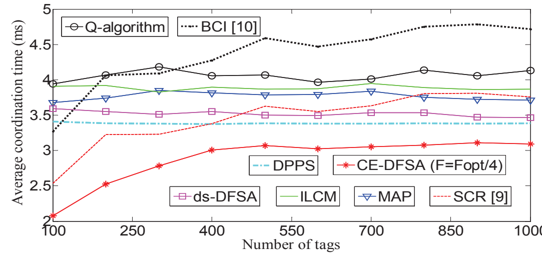

Fig. 4. Simulation results: average coordination time for various algorithms

Q-algorithm, Q-algorithm, ILCM, MAP, ds-DFSA, SCR [9], and DPPS spend 4.3584, 4.0615, 3.8849, 3.7687, 3.5196, 3.4557, and 3.3831 ms, respectively. The CE-DFSA consumes less coordination time than other algorithms.

It is also found that limited by the estimation accuracy in our algorithm, the time efficiency of CE-DFSA under $F = F_{opt}/4$ shown in Fig. 3 has 30.34% loss in comparison with the result under perfect condition shown in Fig. 2.

V. CONCLUSION

In this paper, a collision-tolerant based anti-collision algorithm has been proposed to significantly improve the identification performance of a RFID system. The tag randomly selects a WS from its memory bank to respond to the reader at a specific time slot. Since the WS set is designed for mutually orthogonal, the reader is potentially able to separate the collided WSs and to identify the tags during a collision slot. Performance comparisons have shown the advantages of our proposed algorithm in achieving better time efficiency and lower average coordination time to identify tags.

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