# Idle Slots Skipped Mechanism based Tag Identification Algorithm with Enhanced Collision Detection

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## Abstract

In this article, a new Aloha-based tag identification protocol is presented to improve the reading efficiency of the EPC C1 Gen2-based UHF RFID system. Collision detection (CD) plays a vital role in tag identification process which determines the efficiency of anti-collision protocols since most Aloha-based protocols optimize the incoming frame length based on the collisions in current frame. Existing CD methods are ineffective in identifying collision, resulting in a degradation of identification performance. Our proposed algorithm adopts an enhanced CD (ECD) scheme based on the EPC C1 Gen2 standard to optimize identification performance. The ECD method can realize timely and effective CD by detecting the pulse width of the randomly sent by tags. According to the ECD, the reader detects the slot distribution and predicts tag cardinality in every collision slot. The tags involved in each collision slot are identified by independently assigned sub-frames. A large number of numerical results show that the proposed solution is superior to other existing anti-collision protocols in various performance evaluation metrics.

***Keywords:*** RFID, Anti-collision, Collision detection, Slot efficiency

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## 1. Introduction

As one of the widely known wireless communication technology for short distance, radio frequency identification (RFID) has been increasingly interested intelligence industry due to its various merits including low costs, fast recognition, reusability, and contactless [1]. Similar to the Internet of vehicles [2] and Wireless sensor networks (WSN) [3-4], RFID is also an important branch of the Internet of things (IOT) [5-6]. Generally, core parts of an RFID network contain a reader and multiple low-cost tags. A tag is equipped with a unique identifier (ID) or electronic product code (EPC) (In this article we refer to it as the ID) when it is produced. The reader obtains the tag IDs through data exchange between them over a shared channel [7-8]. When more than one tag reply IDs simultaneously to the reader, collision will inevitably occur and none of IDs can be successfully obtained by the reader. Therefore, collision arbitration is an important issue in achieving fast and efficient identification of tags. To tackle such collision problem, various tag identification protocols have been presented. They mainly can be categorized into tree-based and Aloha-based protocols.

The way of dealing with collisions based on tree-based algorithms [9-14] is to use the dichotomy to continuously divide the collided tag set into two disjoint subsets. Such algorithms are considered as a deterministic method but they suffer from high computational complexity [7]. In addition, their identification latency will be higher than Aloha-based protocols, especially when the cardinality of tags is large. As a contrary, the Aloha-based protocols handle collisions based on a random concession mechanism [15-16]. The reader constructs a time frame which contains multiple slots, and then lets tags randomly choose one of these slots to respond. In this way, the reader can effectively reduce the probability of repeated collisions of some tags. Aloha-based protocols have now become the mainstream solution of EPC C1 Gen2-based RFID system since its simplification to implement. Particularly, the dynamic framed slotted Aloha (DFSA) protocol is an important representative concerned by researchers [17-19].

In many earlier DFSA protocols [17-19], the tag cardinality (unread tags) is required to be accurately estimated so as to optimize the frame length and to improve reading efficiency as much as possible. In order to ensure that the estimation results are accurate and reliable, various prior arts incur huge computational costs. However, not all readers are highly equipped, that is, in order to reduce costs, many readers only have single-core processors, resulting in limitations in computation overhead. Therefore, those anti-collision strategies based on the estimation function may affect the actual identification efficiency due to its high calculation complexity.

To reduce the calculation complexity, many anti-collision work have been proposed recently to achieve low energy consumption [20-22]. Literature [20] proposed an anti-collision protocol (FEIA) that is very intuitive and easy to implement. However, because the frame length updating mechanism of FEIA is based on the observation results of every time slot, its performance is affected by the state of initial time slot.

The authors in [21] proposed an anti-collision protocol namely (ILCM) based on low-cost estimation function which only requires to run some simple mathematical operations. Nonetheless, since ILCM's estimation function is based on interpolation, its performance is not always robust to various number of tags. The literature [22] explored random binary splitting method to deal with collisions during tag identification process, and

proposed a splitting binary based anti-collision protocol (SpBTSA). The slot efficiency of SpBTSA can be improved to about 42.9%. However, the implementation of SpBTSA requires additional hardware costs, that is, a random number generator and a counter need to be added at the tag side. The authors in literature [23] presented an anti-collision protocol namely Multiple-bits-slot reservation aloha (RSMBA) by using reservation mechanism. In essence, RSMBA combines Aloha and Query tree protocols. In the slot reservation phase, the RSMBA protocol uses the collision bit detection mechanism of the query tree protocol, which requires the complex protocol structure.

In this paper, we design an enhanced collision arbitration protocol complying with EPC C1 Gen2. Compared to the most prior arts, there are two advantages in our proposed solution. Firstly, the algorithm eliminates the idle slots during the tag identification reducing the identification time. Secondly, the reader immediately assigns the sub-frame for the collided tags in a slot. The size of sub-frame depends on the width of the random pulses transmitted by tags in a collided slot. The remainder of this paper is organized as follows. In section II, we describe the related works of EPC C1 Gen2 RFID system. Section III introduces our proposed algorithm in detail. In section IV, performance evaluation results of the proposed scheme obtained by simulation are presented. In section V, the conclusions are drawn.

## 2. Related Work

In DFSA, the communication behind the reader and involved tags is accordance with the EPC C1 Gen2 standard. Specifically, in the tag identification process, the link timing follows a time division multiplexing mechanism, that is, time is divided into multiple consecutive frames. And a frame can be further divided into several time slots. The reader sets the length $F$ of the frame by broadcasting the Query command, thereby starting a round of identification. A tag receiving a reader command will randomly pick up one of the $F$ slots to respond. For a specific time slot, it may occurs in three possibilities: idle (no tag response), success (exactly only one tag response), and collision (multiple tag responses). After the reading of the frame, the reader uses the statistics of slots to estimate the number of remaining tags. As long as a collision can be detected in one frame, the reader will update the frame length and start the next round of identification. Considering that $n$ tags are identified by the anti-collision protocol whose initial frame length is $F$, the slot efficiency can be calculated using binomial distribution.

According to the EPC C1 Gen2 standard, the frame length can only be a power of $Q$ to 2, where Q is an integer between 0 and 15 [20], hence EPC C1 Gen2-based DFSA can hold an asymptotically slot efficiency of 0.368 when the value of tag cardinality is same as the frame length ($F=n$). Therefore, for the purpose of achieving a robust slot efficiency, it is necessary to monitor whether the frame length is appropriate in each identification process. Many state-of-the-arts [17-19] have addressed this issue by improving the accuracy of the estimations at the cost of high computation overhead. It is worth noting that due to the low-cost features of passive RFID systems, these protocols with high computational complexity are not very suitable [17].

### 2.1 ILCM

The authors in [21] proposed a tag cardinality estimation method namely Improved Linearized Combinational Model (ILCM) which only requires to run some simple mathematical operations. The anti-collision protocol based ILCM is straight and easy to

implement. The function of ILCM is to obtain the number of tags need to be identified with a modest calculation by using interpolation methods. The work flow of an anti-collision protocol based on ILCM can be given in Fig. 1. An identification round is initialized by the reader's query command which contains a key parameter $Q$ to specify the length of frame (given as $F=2^Q$). When a full frame is read, the reader estimates the number of remaining tags based on the slot statistics ($S$ corresponds to the number of success slots, $E$ corresponds to the number of idle slots, $C$ corresponds to the number of collision slots). Then, the tag cardinality before this round of identification can be calculated with Eq. (14) in [21]. After estimating the tag number, the reader can perform the reading process iteratively until no collision occurred.

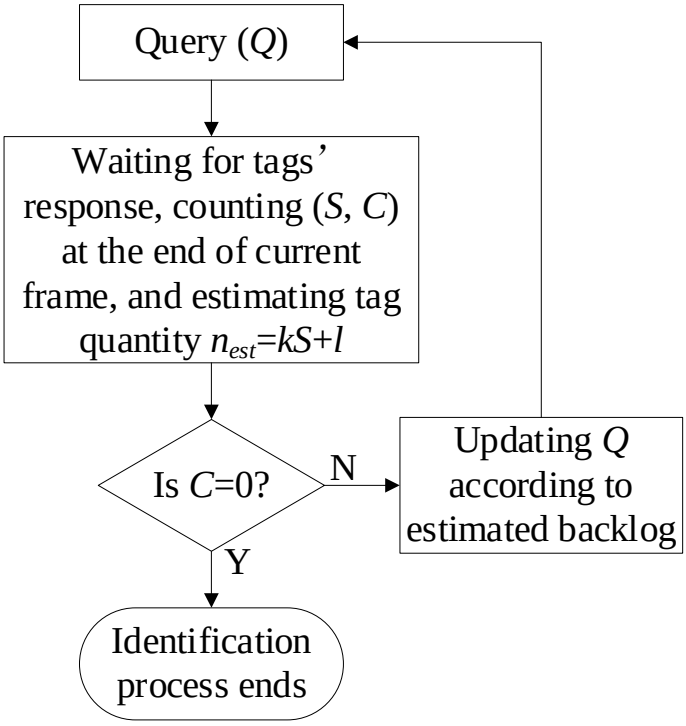


**Fig. 1.** The work flow of ILCM presented in [16]

Compared with those estimation methods with high calculation overhead, ILCM requires only some simple mathematical operations. However, the estimation function of ILCM is derived based on interpolation, so it cannot always maintain robust performance. Once a bit estimation error occurs, the identification performance may be dramatically degraded.

## 2.2 FEIA

The literature [20] made a conclusion that using an estimation function with high calculation complexity to improve tag identification performance is not a very desirable solution. Through simulation results analysis, the estimation accuracy has little effect on the improvement of identification performance. Then, literature [20] proposed a very simple method namely feasible and easy-to-implement anti-collision algorithm (FEIA) for estimating the tag cardinality, which is based on slot-by-slot status observation, i.e., the

reader estimates the remaining tags at every slot of a frame. The work flow of FEIA is plotted in **Fig. 2**.

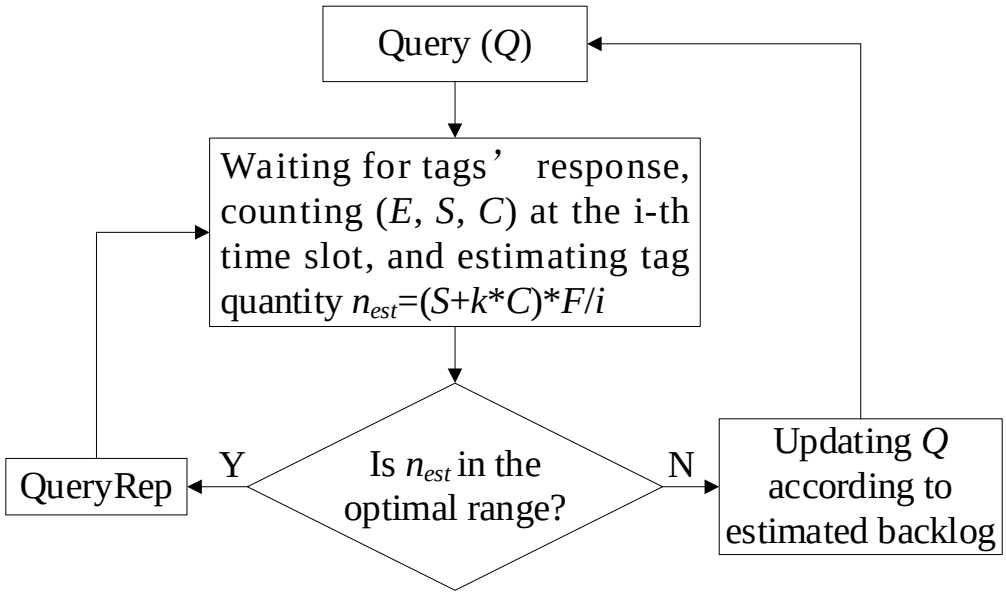


**Fig. 2.** The work flow of FEIA presented in [16]

The workflow of FEIA protocol is that the reader counts the number of idle ($E_i$), success ($S_i$), and collision ($C_i$) slots occurred from the first time slot to the current time slot. The estimation result of tag cardinality is expressed as nest=(Si+k*Ci)*(F/i) where k is a constant value which is obtained as 2.39 by the existing Schoute's method [15]. Compared to the previous estimation functions, FEIA is very intuitive and straight. Its disadvantage is that such estimation function needs to be executed frequently in a frame, that is, formula (3) is executed once in each time slot in a frame, so it also generates high calculation complexity. In addition, the FEIA protocol also has a failure boundary condition, that is, when the initial time slot is idle, the result calculated by formula (3) is 0, resulting in an invalid estimation result. In [24], the partial in-frame adjustment strategy is introduced in the RFID ant-collision procedure. The author proposes an enhanced version of FEIA.

### 2.3 SpBTSA

Combining the advantages of DFSA protocol and binary tree protocol, the literature [22] propose an anti-collision algorithm called SpBTSA. In SpBTSA, the reader uses the frame-like idea to split the tag set into many subsets. There are three possible outcomes for each subset, namely idle, collision, and success, respectively. Different from the conventional Aloha-based protocols, the SpBTSA does not ignore a collision slot, but uses the binary splitting method to directly process the tags involved in the collision slot. Because the SpBTSA does not need to estimate the number of remaining tags, its identification performance will not be affected by the estimation error. In particular, when the length of initial frame is close to the size of tag cardinality to be identified, the slot efficiency of SpBTSA can approach 0.425. However, the implementation of SpBTSA requires additional hardware costs, that is, a random number generator and a counter need to be added at the tag side. Besides, the idle slots and the corresponding coordination time are wasted in the

SpBTSA as the same as other DFSA algorithms. Next, an collision arbitration protocol enhanced collision detection (ECD) is proposed. The ECD protocol is committed to obtaining the slots distribution in advance at the lowest cost, so that it can effectively eliminate idle time slots and deal with the collided tags by assigning the individual sub-frame.

## 3. The proposed anti-collision algorithm based enhanced collision detection scheme

### 3.1 Algorithm description

We develop an effective collision avoidance or anti-collision protocol in this section: namely Dynamic framed slotted Aloha based on enhanced collision detection (ECD). For the ease of description, we have summarized some of the new notations and commands in the article, which are described in **Tables 1** and **2**, respectively.

**Table 1.** Notations

| symbol | Description |
|---|---|
| $F_{ini}$ | Frame size: the number of available slots included in an initial frame |
| Slot_idx | Slot index: 1≤slot_index≤F |
| Sel_idx | The index number of slot reserved by a tag |
| *TSIC* | Tag's slot index counter used to match the parameter slot_idx in reader commands |
| *TSC* | Tag's slot counter used on randomly select a slot |
| *RFG* | Reader flag bit indicates the slot status: 1 represents collision, 0 represents success |
| $F_{sub}$ | The sub-frame size used for identifying collided slots on the reader side |
| $T_{pri}$ | backscatter-link pulse-repetition interval |

**Table 2.** Commands

| Command | Definition |
|---|---|
| CMD_Sel (*F*) | Initializes a command to record the index numbers of sub-slots subscribed by the tags. The command is only used in an initial frame. |
| QueryR (slot_idx, *RFG*) | The reader queries a certain slot whose index number is slot_idx. If *RFG* is 0, the tag replies to the reader with RN16. Otherwise, the tag transmits a pulse among sub-slots whose fixed length is four. The command is used in initial frame. |
| QueryAdj (slot_idx, $F_{sub}$) | The reader queries tags in a collided slot with a small frame size of $F_{sub}$. The command is used in sub-frames |
| QueryRep (slot_idx) | The reader queries a certain slot whose index number is slot_idx. The command is used in sub-frames. |

Before elaborating our proposed protocol in detail, let us briefly introduce the RFID system model. In order to make our proposed protocol more suitable for practical scenarios, we adopt the transmission model defined in ultra high frequency (UHF) industrial standard,

i.e., EPC C1 Gen2. **Fig. 3** specifies the timing to be followed when the reader communicates to the tags within its vicinity for our proposed ECD and conventional DFSA protocol, respectively. In our proposed algorithm, the reader sends a CMD_Sel, QueryAdj and QueryRep command to initiate an identification process, sub-frame and slot, respectively. In **Fig. 3**, T1 represents the time duration needed from the reader to send a command to receive a tag response, T2 represents the time duration needed from the reader to successfully decode the responding data from the tag, T3 represents the guard time needed by the reader to send a new command after T1. $T_{RSV}$ and $T_{ECD}$ are the time used for slot reservation at the beginning of the identification process and the time used for predicting the number of tags in a collided slot by enhanced collision detection, respectively.

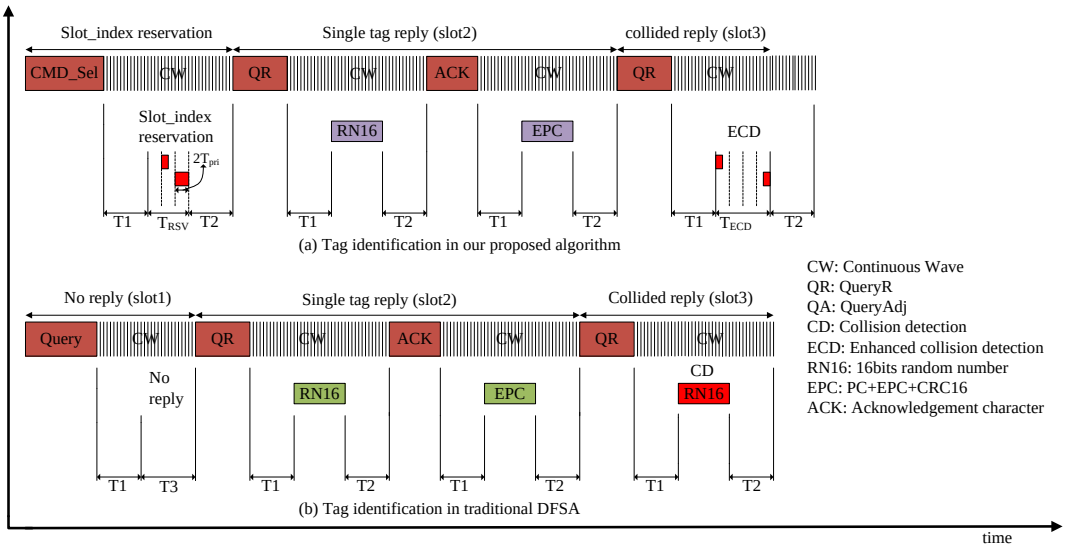


**Fig. 2.** Link timing between the reader and tags

## 3.2 Working of ECD

In the execution process of ECD protocol, the reader maintains a stack to record three parameters including slot_idx, Col_idx and $F_{sub}$. At the beginning of identification, the reader initiates a CMD_Sel command. Then, the reader issues a QueryRep (slot_idx) command to probe each slot. For a tag, it first sets its working mode to inactive and then performs the following operations according to the reader instructions:

(1) **Slot_index reservation:** When receiving the CMD_Sel ($F_{ini}$) command from the reader, a tag transmits a pulse with a duration of $T_{pri}$ in a randomly selected sub-slot whose period is $2T_{pri}$, among total $F$ sub-slots. In this paper, sub-slot is different from the slot in conventional DFSA protocols. It is only used for pulse transmission and detection, not for identifying the tag ID. Where $T_{pri}$ represents backscatter-link pulse-repetition interval. The reader monitors the pulses transmitted by tags sub-slot by sub-slot. A idle slot will be indicated if no pulse is detected. According to the slot_index reservation, the idle slots can be skipped by the reader at the step of identification.

(2) **Sub-frame schedule:** For each slot reserved, when a collision is detected, the reader will assign a relatively small sub-frame for the collision slot to resolve the collided tags. By using the QueryR command to detect the width of pulses, the reader can identify a collided slot. After receiving the QueryAdj (Col_idx, $F_{sub}$), an active tag compares its

*TSC* with Col_idx. If TSIC=Col_idx, the tag randomly selects a slot within $F_{sub}$ slots called sub-frame and respond to the reader.

(3) **Slot identification:** After receiving the QueryR (slot_idx, *RFG*) command, a tag respond to the reader with its ID if *RFG* is 0. And the tag will be identified successfully. Otherwise, the tag transmits a pulse with a duration of $T_{pri}$ among sub-slots, where the number of sub-slots is fixed as four.

The anti-collision protocol is based on the reader-talk-first mode. For the reader, the entire identification process can be divided into six procedures.

(1) The reader initiates an identification process by broadcasting a CMD_Sel ($F_{ini}$) command. The command parameter *F* means that the number of sub-slots equals to *F*.

(2) Each tag within the reader vicinity randomly picks up a sub-slot and transmit a pulse during the selected sub-slot. The reader monitors the pulse sequence transmitted by the tags: whether there is zero, one, or multiple pulses. A collision will be indicated if the pulse width is above $T_{pri}$. Similarly, a idle slot will be indicated if no pulse is detected. We make a reasonable assumption that when multiple tags send pulses in a sub-slot simultaneously, the reader can detect through a sliding window that the mixed pulse width is wider than a single pulse width. Due to deviations in the frequency of the backscatter links of the tags, the tags' pulses do not reach the reader side completely synchronously. So, the assumptions in our proposed ECD are reasonable and feasible. After receiving the pulse sequence from the tags, the reader can easily recognize the slot distribution.

(3) The reader queries tags in the non-empty slots. In other words, all idle slots in this stage can be avoided. The reader transmits a QueryR (slot_idx, RFG) command to all of tags and waits for receiving a response from a tag. It may have the following two situations. One is that there is exactly one tag to reply, then it can be successfully recognized by the reader. The second is that multiple tags reply to the reader simultaneously, and a collision will occur at this time. Meanwhile, the reader predicts the number of tags in a collided slot according to the width of pulses transmitted by the tags. It is noted that the involved tags will not transmit their IDs information to the reader at this stage.

(4) After the reading of $F_{ini}=F$ slots (idle slots are skipped), the reader counts the slot_idxs of all collided slots and assign the corresponding sub-frame size for each collided slot. In this step, the slot_idxs of all collision slots are stored in a stack.

(5) The reader sends a QueryAdj (slot_idx, $F_{sub}$) command to provide a small frame length for the corresponding tags in a collision slot. By extracting the parameter $F_{sub}$, each tag randomly picks up a time slot from $F_{sub}$ slots and responds to the reader. The tag whose slot counter is equal to 0 will respond to the reader immediately. The identification process is the same as that of traditional DFSA algorithm.

(6) Repeat step 5 until the stack is empty, which indicates all tags are successfully identified. The whole identification process ends.

### 3.3 An example

An identification example is shown in **Fig. 4** to illustrate the tag identification process of the proposed ECD. Assume that the four tags to be identified in an RFID system are A, B, C, and D. Set an initial frame size $F_{ini}=F=4$. The whole identification procedure can be divided into two phases: Initial frame phase and sub-frames phase. The detailed identification steps are as follows.

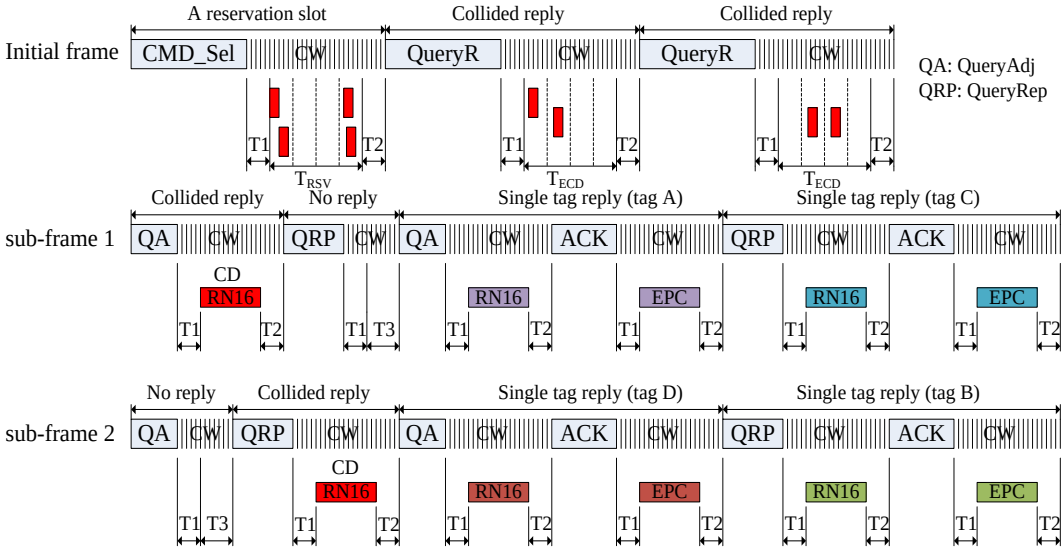


**Fig. 4.** An identification example of the proposed ECD

(1) The reader transmits a CMD_Sel command to start an initial frame. At the beginning of the identification process, the reader sends a CMD_Sel command with $F$ (here $F=F_{ini}=4$) sub-slots to allow each tag to transmit pulse in a randomly selected sub-slot.

(2) After receiving the CMD_Sel command, each tag sends a pulse with a length of $T_{pri}$ to the reader during a randomly selected sub-slot whose duration is $2T_{pri}$. Tag A and tag C send the pulses during the first sub-slot. Tag B and tag D send the pulse during the fourth sub-slot. According to detect the width of the pulses transmitted by the tags in the reservation slot, the reader distinguishes that slot1 and slot4 are collided, slot 2 and slot 3 are idle. Therefore, in the next step the idle slots can be skipped.

(3) The reader transmits the QueryR command to predict the number of involved tags in slot1. Upon receiving the QueryR command, the tags A and C transmit the pulses in first and second sub-slot, respectively. Then the reader predicts there are two tags in the slot1 by detecting the width of pulses. Similarly, the reader predicts there are two tags in the slot4. Therefore, the reader will assign a sub-frame whose size is 2 to resolve the collided tags.

(4) The reader sends QueryAdj (1, 2) command to queries tags collided in slot1 during the initial frame. After receiving the command, each tag randomly picks up a time slot between 1 and 2 and responds to the reader. In the first round, tags A and C are collided in slot 1. Hence, another round is required. In the second round, two slots are single occupied. After the reading of two rounds, corresponding to four slots, Tags A and C are have been identified in success. The tag reading process is the same as that of other DFSA algorithms.

(5) Similar with the step (4), the reader consumes four slots to identify tags B and D. The above steps (1) to (3) forms initial frame phase, and steps (4) to (5) forms sub-frames phase.

### 3.4 Brief of analysis of ECD

Compared to the DFSA algorithms in EPC C1 Gen2 standard, our proposed algorithm can be

performed efficient in the following two ways: (1) According to the custom command CMD_Sel and pulse detection mechanism, all of idle slots can be skipped to save the identification time. (2) ECD is utilized to predict the number of collided tags at the low cost since a time duration $T_{pri}$ for one pulse transmission is less than 1-bit period in the RN16, the pulse detection time $T_{ECD}$ is very short compared with the RN16. (3) Assigning an individual sub-frame for each collided slot is more efficient than adjusting a new frame size for all collided tags based on the tag backlog (unread tags) estimation. Note that in our scheme, a pulse transmission duration is equal to one subcarrier cycle in the RN16, the period of which is $T_{pri}$ shown in **Fig. 3**. For pulse detection in our algorithm, a square-law detector is adopted at the reader receiver for its effectiveness and design simplicity.

We assume that an initial frame of size $F=F_1$ is used to identify $n$ tags. Complete reading of the frame, the number of collision slots counted by the reader is $m$ and each slot has $k_i$ ($k_i \geq 2$) tags, the number of identified tags is $n_1$. We assume that the remaining tags ($n_2$) can be identified with the frame of size $F_2$. The average slot efficiency of traditional DFSA algorithm is expressed as:

$$U = n / \left[ \frac{F_1}{\left(1-1/F_1\right)^{n_1-1}} + \frac{F_2}{\left(1-1/F_2\right)^{n_2-1}} \right] \tag{1}$$

Intuitively, the throughput reaches its peak value when the frame length equals to tag population. Hence, the maximum throughput of DFSA can be given as

$$U_{\max}^{DFSA} = F / \left[ \frac{F}{\left(1-1/F\right)^{F-1}} + \frac{\sum_{i=1}^{m} k_i}{\left(1-1/\sum_{i=1}^{m} k_i\right)^{\sum_{i=1}^{m} k_i - 1}} \right] \tag{2}$$

Considering the same conditions, the throughput of the proposed ECD can be written as:

$$\begin{aligned} U^{DFSA-ECD} = F / [ & \frac{F}{\left(1-1/F\right)^{F-1}} - F\left(1-1/F\right)^{F} \\ & + \sum_{i=1}^{m} \frac{k_i}{\left(1-1/k_i\right)^{k_i-1}} ] \end{aligned} \tag{3}$$

Compared Eq. (2) to Eq. (3), it is can be concluded that the system throughout of ECD is higher than other DFSA algorithms since the function of $(1\text{-}1/k)^{k\text{-}1}$ is a monotonically decreasing function. For a collided slot with two tags, its slot efficiency can achieve at 0.5, which is greater than 0.368 of traditional Aloha-based algorithms. In order to maximize the efficiency of the proposed ECD, we hope each collided slot only contains two tags. We define the expected number of tags involved in a collided slot $n_c$ as follows.

$$n_c = \frac{n - F \cdot E(s)}{E(c)} \tag{4}$$

herein $E(s)$ and $E(c)$ denoted as the expected value of the number of success and collision slots, respectively. Let $n_c$ equals to 2, we have

$$\frac{n - n\left(1-1/F\right)^{n-1}}{F - n\left(1-1/F\right)^{n-1} - F\left(1-1/F\right)^{n}} = 2 \tag{5}$$

From Eq. (5), the $F$ is approximately equal to the twice size of $n$. Although the initial frame length is set to twice of the number of tags, it does not degrades the performance due to the elimination of idles slots during the initial frame phase as described above. Hence, the performance is dramatically improved by using pulse width detection method and individual sub-frame size for each collided slot. Coincidentally, ECD also suffers from several shortcomings. The slot efficiency of ECD is also sensitive to the initialized frame length $F_{ini}$. In most RFID application scenarios, the reader does not have prior knowledge about the tag cardinality before identification. Specifically, in our work, to estimate the tag cardinality, the reader issues an initial frame size of 1/q, but terminates it at the end of the first slot. And then the reader repeatedly performs such single-slot frames while reducing q with a geometric distribution (i.e., q=1/(2i-1) in i-th frame) until the reader gets an empty slot. Assume that the first idle slot appears in the i-th frame, the tag cardinality can be estimated as 1.2897×2i-2 [27].

## 4. Performance analysis and simulation results

In this section, we theoretically and experimentally analyze the performance of the protocol presented in this article [26]. The performance evaluation metrics we consider include slot efficiency, time efficiency, and average identification rate. Based on specifications of EPC C1 Gen2 standard, the time efficiency $T_{effi}$ can be defined by

$$T_{effi} = \frac{S \cdot T_{succ}}{T_{slots} + T_{exa}} \tag{6}$$

$$T_{slots} = S \cdot T_{succ} + E \cdot T_{idle} + C \cdot T_{coll} \tag{7}$$

$$T_{exa} = T_{CMD\_Sel} + T_1 + T_2 + T_{RSV} \tag{8}$$

where $S$, $E$, and $C$ denote the number of success, idle, and collided slots of an identification process, respectively. $T_{exa}$ is the extra time used for slot reservation, where $T_{RSV}$ ($F$*$2T_{pri}$) is the processing time of pulse detection. $T_{succ}$, $T_{idle}$, and $T_{coll}$ are the time durations for each slot type above and have:

$$T_{idle} = T_{cmd} + T_1 + T_3 \tag{9}$$

$$T_{succ} = T_{cmd} + 2(T_1 + T_2) + T_{RN16} + T_{ACK} + T_{PC+EPC+CRC} \tag{10}$$

$$T_{coll}^{1} = T_{cmd} + T_1 + T_{ECD} + T_2 \tag{11}$$

$$T_{coll}^{2} = T_{cmd} + T_1 + T_{RN16} + T_2 \tag{12}$$

herein $T_{cmd}$ is defined as the time duration of reader's query commands including Query, QueryR, QueryAdj, and QueryRep. $T^{1}_{coll}$ denotes the time interval needed for a collision slot during the initial frame phase where $T_{ECD}$ is (8*$T_{pri}$) the processing time of pulse detection, $T^{2}_{col}$ denotes the time duration of a collision slot during the sub-frame phase.

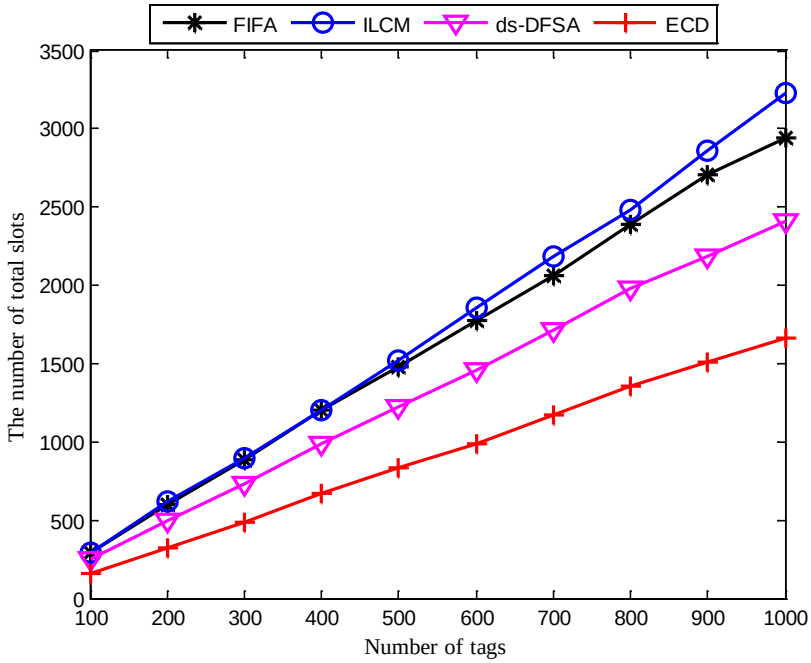


**Fig. 5.** Comparison of the number of total slots for various algorithms

Since each pulse is transmitted in a randomly selected sub-slot, a situation exists where more than two pulses are distributed into a same sub-slot. Under this situation, the reader is unable to exactly identify the number of pulses. This situation will degrade the identification performance. However, the performance degradation can be neglected since the number of collided tags in a slot is small. For the purpose of evaluating the performance of the proposed ECD protocol, we compared the proposed ECD with existing work including FIFA [23], ILCM [21], and ds-DFSA [25] through multiple independent computer simulations. The scenario used in computer simulations is a single reader and a large number of passive RFID tags. The channel environment is considered ideal, that is, all tags can receive commands from the reader accurately. The simulation scenario is as same as that in the previous literatures [17-20]. In all of simulations, the tag cardinality is range from 100 to 1000. All the experimental results described in this article are run on a laptop computer. The specific configuration of the laptop is an i5 CPU and a 4G memory. The parameters used in MATLAB simulations is same as [23].

**Fig. 5** reports the experimental results in terms of total number of slots for comparative protocols when the tag cardinality increases from 100 to 1000. Observed from the **Fig. 5**, we can see that ECD protocol consumes the least number of slots to identify the same batch of tags compared to other algorithms. For example, to identify 1000 tags, the proposed ECD protocol consumes only 1662 slots while FIFA, ILCM and ds-DFSA consumes 2943, 3233 and 2411 slots. The reason is that the proposed ECD can completely remove the empty slots and significantly reduce the number of collision slots by pulse detection mechanism. The ECD reduce the total number of slots over the previous compliant Aloha-based algorithms by an average of 41.5% for uniformly distributed tag populations.

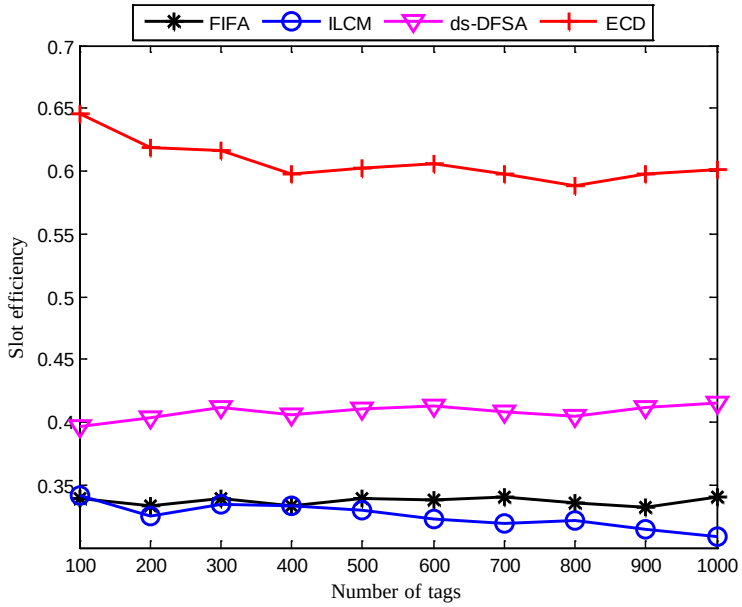


**Fig. 6.** Comparison of slot efficiency for various algorithms

**Fig. 6** plots the slot efficiency of all comparative approaches. Based on the definition and description of the prior arts, the slot efficiency can be calculated as a ratio that the number of slots required to identify a batch of tags divided by the total number of the tags of the batch. Similar to the results in **Fig. 5**, the proposed ECD always peaks up the best slot efficiency compared to other reference methods, and the mean value of slot efficiency is close to 0.6 when the size of tag cardinality is greater than 500. By pulse detection mechanism, the proposed ECD can easier to identify unread tags. The unnecessary idle slots and collision slots can be avoided, thus the slot efficiency is greatly improved. As a specific, the ECD algorithm is superior to comparative approaches and improves the normalized slot efficiency over other compliant EPC C1 Gen2-based DFSA protocols by an average of 70.2%.

## 5. Conclusion

In this paper, we discuss the impact of the collision detection on the RFID performance. Existing Aloha-based algorithms mainly improve the identification efficiency by estimating the number of unread tags and then setting an optimal frame size as much as possible to avoid the collision ratio. The collision detection method is not fully exploited. Our proposed algorithm adopts an enhanced collision detection scheme based on the EPC C1 Gen2 standard to improve identification efficiency. According to the introduced collision detection method, the empty slots can be removed and the collisions slots can be further reduced. Numerical results verify that the proposed ECD protocol outperforms the prior arts in terms of various metrics.

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