Identifying RFID Tags in Collisions

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Abstract—How to obtain the information from massive tags is a key focus of RFID applications. The occurrence of collisions leads to problems such as reduced identification efficiency in RFID networks. To tackle such challenges, most tag collision arbitration protocols focus on scheduling tag identification with collision avoidance. However, how to effectively identify tags in collisions to improve identification efficiency has not been well explored. In this paper, we propose a group query allocation method to divide the string space into mutually disjoint subsets which contains several strings. Each string can be viewed as a full ID or partial ID of a tag. When multiple string from a subset are sent simultaneously, the reader can identify all of them in a time slot. Based on the group query allocation method, a segment detection based characteristic group query tree (SD-CGQT) protocol is presented for fast tag identification by significantly reducing the collision slots and transmitted bits. Numerous experimental results verify the superiority of the proposed SD-CGQT, compared to prior arts in system efficiency, total identification time, communication complexity and energy consumption.

Index Terms—RFID, tag identification, characteristic group, group query, system efficiency, communication complexity.

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1 INTRODUCTION

1.1 Background and Problem Statement

RADIO frequency identification (RFID) is a backscatter communication technology for automatic object identification and has been widely used in access control, supply chain monitoring and warehouse management and other fields [1-3]. An RFID system consists of a reader and many low-cost tags with constrained computing power. A tag with an unique identifier (ID) is attached to an object and thus, can be identified by the reader. An objective of RFID systems is to quickly identify all the tags in the reader's vicinity. However, since the communication channel is shared between the reader and tags, tag collision occurs when more than one tag respond to the reader simultaneously, which not only leads to tag data retransmission but also worse identification efficiency in terms of transmission time and energy [4]. Therefore, an efficient tag collision arbitration protocol (also named anti-collision or tag reading protocol) is crucial for RFID systems. Because RFID tags have ultra-low computing capability, typical MAC protocols wireless network cannot be used in RFID systems.

RFID collision arbitration protocols fall into two categories, namely Aloha-based [5-8] and Tree-based protocols [9-13]. In Aloha-based protocols, the reader probes tags by sending a query command with parameter F (named frame length) and a tag replies a query with its 16-bits random number (RN16) at a randomly selected time slot in a frame [14]. The reader determines the status of a time slot by decoding the RN16s. For a given slot, it has three possible status, i.e., singleton (exactly one tag replies with RN16), empty (no tag replies with RN16), and collision (multiple tags reply with RN16s). After reading a frame, the reader takes advantages of slot statistics to estimate the tag cardinality (the number of unread tags). The key design principle of Aloha-based protocol is to adopt an appropriate frame update mechanism in the tag identification process based on the estimated cardinality. Many prior work [10-11] focus on tag cardinality estimation methods in order to approximate the maximal access probability of 0.368 [15].

Tree-based protocol essentially subdivides the colliding tag set into smaller groups until a single tag response is successfully identified by the reader. Generally, tree-based protocols can be further divided into Query tree (QT) [16-17] and Binary splitting (BS) [7-9] protocols. Among them, QT protocol is a typical memoryless protocol. Memoryless means that the tags need not have additional memory except ID for identification [17]. In QT protocols, the reader probes tags with a binary string (called query prefix), and the tags whose IDs match the query prefix will respond. If detecting a collision, the reader will probe tags again after appending the previous query prefix by 0 and 1, respectively. This query-and-append loop continues until all

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Digital Object Identifier xxxx

tags are successfully identified.

1.2 Limitations of Prior Art

The key limitation of the existing collision arbitration protocols is that they cannot effectively identify tags in collision slots. For Aloha-based protocols, each tag uses RN16 to compete for the shared channel. Once a collision is detected, the reader cannot decode any useful transmission. The tag has to re-transmit its ID information in subsequent slots. In addition, the reader needs to use the statistical value of collisions to estimate the number of remaining tags. Hence, Aloha-based protocols cannot prevent collisions due to its randomness and thus unable to identify tags in any collided slots. For QT-based protocols, each tag uses its ID to compete for the shared channel. If a collision happens, the reader needs to generate new prefixes for the following queries using collided ID string. Most of the existing tag identification protocols focus on reducing collisions and the signals received during collision are discarded, which limits the performance of tag identification.

1.3 Proposed Approach

In this paper, we make the first step forward using collided signals to improve reading performance. Specifically, we allow a particular group of tags respond to a particular query, so that each collision bit represents one and only one tag's existence. Based on the mixed signals from tags, the reader can recover them and identify the corresponding tags. The following example explains the basic idea of our approach. As shown in Fig. 1, there is a group of four tags with IDs (characteristic codes are serviced as IDs here) of “0001”, “0010”, “0100”, and “‘1000”, respectively. All of these IDs are only one bit different from the query prefix “0000”. When more than one tag from the group respond simultaneously, the reader can still identify them successfully according to collision information. Suppose that the tags with IDs “0010”, “0001”, and “0100” respond, and the received string at the reader side is “0xxx”, where the 2nd, 3rd, and 4th “x” represent collided bits. Since transmitted IDs has only one bit different from the query prefix, the reader can performs $0000 \oplus 0100$, $0000 \oplus 0010$, and $0000 \oplus 0001$ operation, respectively, according to the location of collided bits, where $\oplus$ means XOR operation. Then, the reader can decode the responding IDs as “0100”, “0010”, and “0001”, respectively. Accordingly, the reader can identify multiple tags with only one query in a slot. Thus, the proposed approach can significantly improve the reading performance over the existing anti-collision protocols.

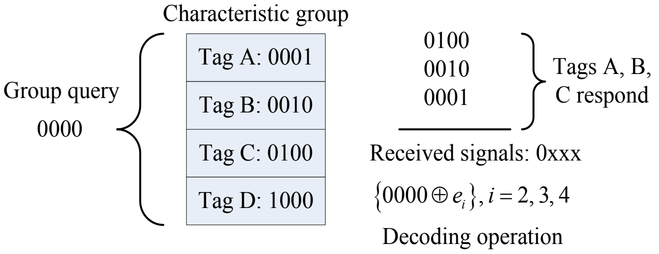


Fig. 1. An illustrative example of the proposed approach

1.4 Technical Challenges and Solutions

The first technical challenge is on classifying the entire tag set into a number of groups where each group can be probed by a particular binary query. We address this challenge by designing many groups of special codes (named characteristic code) for tags in MAC layer based on a particular rule that the characteristic codes in each group are all one bit different from the particular query prefix (named group query). A characteristic code is a string of symbols transmitted by a tag, whose length can only be a integer power of 2.

The second technical challenge is on extending the proposed approach to the scenarios where tag ID length is long and not an integer power of 2. We address this challenge by proposing a segment (the length of segment is strictly an integer power of 2) detection mechanism to reduce the extra empty queries and limit the transmitted bits in collisions. Leveraging the characteristic code design and segment detection mechanism, the proposed approach can significantly improve the reading performance over the existing anti-collision protocols.

1.5 Summary of Experimental Results

We evaluated our SD-CGQT in MATLAB R2012b over extensive Monte Carlo simulations. The SD-CGQT significantly improves the reading performance over previous QT-based algorithms. When the number of tags varies from 20 to 200 with 8 bits ID length, experimental results show that our SD-CGQT protocol significantly outperforms the best prior QT-based protocols in terms of system efficiency, total identification time, communication complexity, and total energy cost by over 4.24x, 71.5%, 79.8%, and 84.6%, respectively. When the number of tags is ranging from 200 to 2000 with 96 bits ID length, experimental results show that our SD-CGQT protocol outperforms the best prior QT-based protocols in terms of total identification time, communication complexity, and total energy cost by an average of 30.3%, 30%, and 27.9%, respectively. When the number of tags varies from 20 to 200 with 96 bits ID length, experimental results show that our SD-CGQT protocol outperforms the best prior QT-based protocols in terms of total identification time, communication complexity, and total energy cost by an average of 27.3%, 27.3%, and 27.9%, respectively.

2 RELATED WORKS

To tackle the tag collision issue in dense RFID networks, many past works [18-19] focus on how to effective reduce the number of collisions and identification time. For instance, STT [18] attempts to use some heuristics to generate prefixes for the following queries based on the results of previous queries. It assumes that tag IDs strictly follow uniform distribution, which may not be always satisfied in reality.

In addition to identification time, energy consumption is also an important issue in RFID tag identification [13]. To this end, the energy consumed in collision arbitration protocols have been studied in the literatures [20-21]. They aim to reduce the energy cost of the reader and tags separately and focus on active tags exclusively, thus are not suitable for passive RFID systems. With reduced price cost, passive tags become popular for large scale deployment and portable readers are increasingly being used, therefore, the energy consumption in passive RFID systems should be also concerned. For passive RFID systems, the main source of energy consumption is on the reader side. The reason is that the reader must not only provide energy to its own, but also energize nearby tags during tag identification process. The amount of energy consumption includes the energy used for energizing tags and coordinating communication between the reader and tags. The former is related to the total identification time, whereas the latter highly depends on the communication complexity, i.e., the average amount (measured in number of bits) of messages per tag identification transmitted by the reader and tags during tag identification process [13, 20, 22, 30]. To improve energy efficiency in passive RFID systems, both identification time and communication complexity should be considered. Recently, many energy-saving protocols have been presented for passive RFID systems to reduce the identification time and communication complexity by adopting the bit collision detection technology [3, 23-24]. The literature [25] proposed an improved version of QT, namely collision tree (CT) protocol, which allows the reader to track the first collided bit in a slot and divide the collided tag set into two disjoint subsets. Although CT can completely remove empty queries in the identification process, it still requires a large number of collision queries and consumes vast transmitted bits for each collision, which increases the communication complexity.

To further optimize the number of queries, some protocols based on M-ary tree have been presented in literatures [26-28]. In [26], a multi-bit identification protocol (MBI) is proposed, in which the reader makes full use of collided bits to identify multiple ID strings of a specific length in the same slot. In MBI, when there are several collided bits in the received string, the reader will activate a special M-slot to recover the received string, thereby reducing the probability of continuing collision in the subsequent slots. The literature [27] proposed a M-ary query tree (MQT) protocol by modeling the tag identification process as an optimal M-ary traversal process. Although MQT can further improve the system efficiency, its communication complexity is also increased because a tag should return the mapped M-bit sequence and ID to the reader at the same time. The authors in literature [28] presented a similar M-ary collision bit based query tree (MCT) protocol for tag identification. In MCT, a multi-bit collision arbitration mechanism is introduced to divide the collided tags into M subsets. Then, the reader constructs a query command with prefix to probe the subsets in sequence. Because the prefix is sent only once in the process of identifying M subsets of tags, the communication complexity of MCT is reduced. According to the analysis in [28], energy consumption is also a critical concern that cannot be ignored and needs to be considered in the design of the anti-collision protocol. To limit the number of transmitted bits from tags, a bit window strategy is introduced [29]. By applied bit window strategy into CT protocol, a collision window tree (CwT) protocol is proposed to decrease the energy cost during identification process. Although CwT reduces the number of transmitted bits per slot, it adds many additional go-on slots, thus increases the total number of slots. Moreover, the head message contained in query commands transmitted by the reader is ignored by the authors. However, such head message is extremely critical and cannot be ignored in tag identification process [19][28-30]. By investigating both bit query strategy and optimal query switching mechanism, a novel tag identification protocol namely bit query based M-ary query tree (BQMT) [30] is proposed to optimize the reading performance of dense RFID network. Benefiting from the bit query mechanism, BQMT can significantly reduce the total number of queries and improve the energy efficiency. However, the BQMT is unable to maintain constant performance under the various scenarios. Most of the previous anti-collision solutions [10-14][24-30] focus on efficiently reducing the number of collisions and decreasing identification latency. They are all based on the assumption that there is only one tag reply for a channel, and collision information will be directly discarded. This undoubtedly wastes a lot of useful information and restricts the further improvement of the efficiency of the anti-collision protocols.

3 PRELIMINARIES: BIT TRACKING AND DEFINITIONS

For the convenience of description, we summarize the symbols and notations used in this paper in Tab. I.

TABLE 1
NOTATIONS USED IN THE PAPER

Symbol	Description
N	The number of tags to be identified
L	The length of tag ID
K	The length of a group query
$\vec{\mathbf{x}}$	A row vector with K-dimension
$\vec{\mathbf{e}_x}$	A unit vector whose x-th bit is 1 and the rest are all 0
$\oplus$	XOR operation
$\lVert\vec{\mathbf{x}}\rVert$	The number of 1 in the vector $\vec{\mathbf{x}}$
$\lvert\vec{\mathbf{x}}\rvert$	The dimension of vector $\vec{\mathbf{x}}$
$S^x = \{0,\ 1\}^x$	A x-dimensional vector space
$\emptyset$	Null set
$\vec{\mathbf{Q}_x} = \&G_x$	A x-th group query associated to x-th characteristic group G_x
$\mathbb{Q}_{ini}$	An initial group query set
$\mathbb{Q}_{out}$	An output group query set
$\vec{\mathbf{g}_x}$	An arbitrary vector belonging to characteristic group G_x

3.1 Bit tracking technology

In this paper, we consider an RFID scenario including a single reader and a number of passive tags. Before tag identification, both tag cardinality (the number of tags to be identified) and ID are unknown for the reader. We focus on finding an efficient solution to tackle the fundamental RFID tag anti-collision problem, namely reading all IDs of a given batch of tags in a time-efficient or energy-efficient way. Especially, we are particularly concerned scenario that dense RFID network using shorter IDs. Because this paper focuses on the multi-tag anti-collision problem, the dense RFID network here refers to a single reader scenario with a large number of tags. The tags with shorter IDs can be applied into many applications such as access or inventory control. For example, an entrance control system is installed at the front of a building or dormitory, which is used for flow control of about 200 people per day. Only tags with 8-bit IDs are required to complete the identification of 256 (2^8) people.

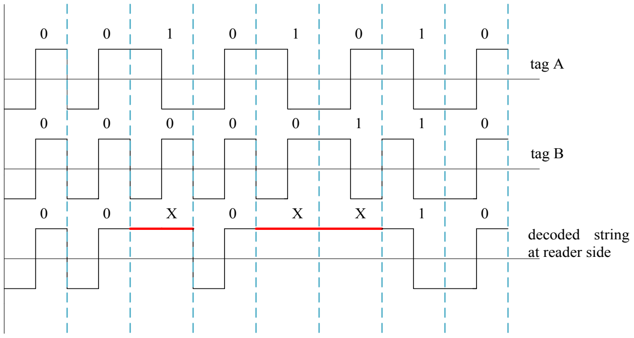


Fig. 2. An illustrated Example of Manchester Code

QT-based anti-collision protocols are more favored by low-cost RFID system [29]. The key component of QT-based protocol is bit tracking technology [1-3]. Bit tracking technology is commonly based on FM0 [31] or Manchester coding, in which the encoding of each data bit is either low-to-high or high-to-low with equal time interval. In such RFID network, a tag transmits data through Manchester coding. As illustrated in Fig. 2, it is feasible to trace individual collided bits by bit tracking technology. In Fig. 2, the IDs of tag A and tag B are "00101010" and "00000110", respectively. When both tag A and tag B choose a same slot to reply with IDs using Manchester coding method, the mixed signal received by the reader is "00x0xx10", where "x" represents a collided bit. The example shows collisions in 3-rd, 5-th, and 6-th bits. For a bit interval, only different data will cause a collision, so the collision can be equivalent to XOR operation in this paper. The information obtained using bit tracking technology helps to further divide the collided tags into subsets during the following identification process, allowing the reader to identify them more efficiently and quickly. It is noted that all tags involved in communication procedure should synchronously return data to the reader. Literature [32] indicated that the synchronization offset of COTS tags usually does not exceed 1 µs, and this offset only accounts for 5.3% of the duration of an individual bit. Therefore, bit-wise synchronization is not a big concern in QT-based protocol. Moreover, literature [33] recently further verified the feasibility of bit-wise synchronization in RFID tag identification by carrying out the practical experiments with USRP and WISP tags. To further verify the feasibility of SD-CGQT, we have carried out the practical experiments with one RFID reader and 10 WISP tags. The experimental setup is shown in Fig. 3. The reader is equipped with ARM Cortex A9 processor, which is a 32-bit reduced instruction set (RISC) processor with a maximum operating frequency of 1 GHz and an off-chip memory 512M to ensure high speed and stable operation of programs. In order to comply with ISO/IEC 18000-6B, the carrier frequency is set to 922.875MHz. The experiments are carried out by placing 10 WISP tags in the coverage of the RFID reader with a fixed transmitting power. Fig. 3(b) shows the individual signal level results from different tags. Since ON-OFF keying modulation is also used in the experiment, each logical bit can be obtained by observing the value of magnitudes. For example, the data from tag 1 are "01100". Fig. 3(c) shows the combined signals when 3 tags send their data simultaneously. As can be observed, the aggregated symbols are "01110", which are the bitwise OR of individual signals from 3 tags. The experiments further verify that the bit-wise synchronization is not a big concern in QT-based protocol and it is feasible to exploit the mixed signals in our algorithm design.

3.2 Definitions

Before describing the proposed solution in this article, we first introduce several definitions which are fundamental design guidelines of the protocol.

Characteristic code and group: In QT-based protocols, a tag replies to the reader with its ID information when the tag's ID matches to the query prefix sent by the reader. In the proposed solution, we introduce a characteristic code for query-response mechanism. The description of characteristic code can be given as follows. Considering a group of characteristic codes, each of which has only one bit different from the query prefix in the reader's query command. When multiple characteristic codes from the set are fed back to the reader simultaneously, the reader can successfully identify them. In this paper, the characteristic code can be used as a full ID or part of a full ID. A group of characteristic codes can be viewed as a characteristic group. Based on the concepts of characteristic code and group, we can derive the following theorem.

Theorem 1. *Assume that a set of tag ID strings is a characteristic group. When multiple tags from this group respond simultaneously, the reader can successfully identify them in a slot according to the features of characteristic group.*

Proof: Suppose there are m tags in a characteristic group responding to the reader simultaneously, and using $\vec{\mathbf{x}}_i$ and $\vec{\mathbf{x}}_j$ to denote two arbitrary ID strings for i-th and j-th tag. Then, we have

$$\vec{\mathbf{x}}_i \neq \vec{\mathbf{x}}_j; (1 \leq i < j \leq m) \tag{1}$$

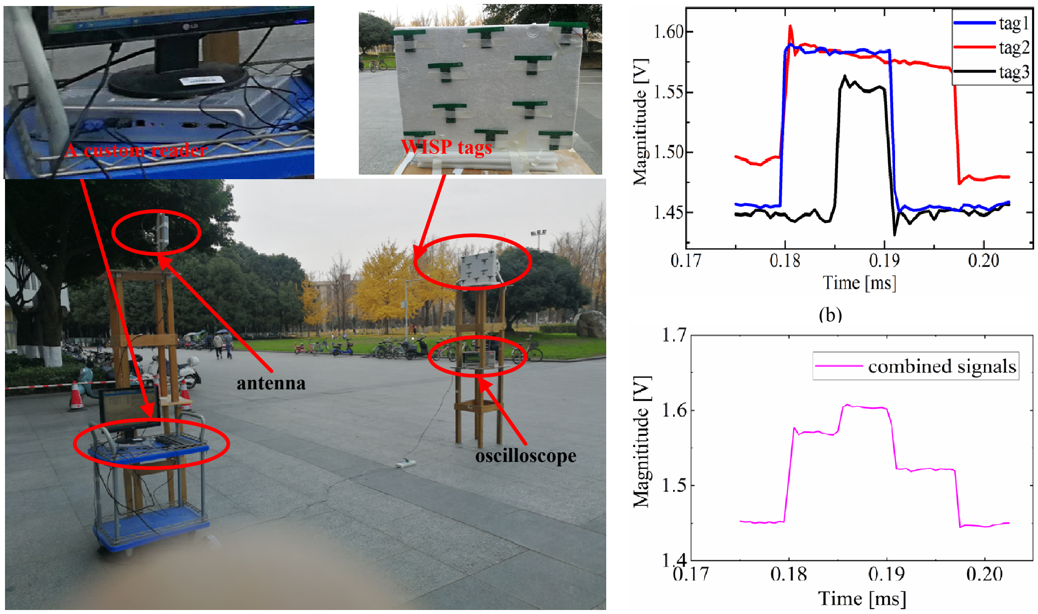
Since both $\vec{\mathbf{x}}_i$ and $\vec{\mathbf{x}}_j$ are only one bit different from the query prefix $\vec{\mathbf{q}}$, we can have

$$\vec{\mathbf{x}}_i = \vec{\mathbf{q}} \oplus \vec{\mathbf{e}}_i,\ \vec{\mathbf{x}}_j = \vec{\mathbf{q}} \oplus \vec{\mathbf{e}}_j \tag{2}$$

When two tags transmit $\vec{\mathbf{x}}_i$ and $\vec{\mathbf{x}}_j$ simultaneously to the reader, the mixed signal $\vec{\mathbf{y}}_R$ can be expressed as

$$\begin{aligned} \vec{\mathbf{y}}_R &= \vec{\mathbf{x}}_i \oplus \vec{\mathbf{x}}_j = (\vec{\mathbf{q}} \oplus \vec{\mathbf{e}}_i) \oplus (\vec{\mathbf{q}} \oplus \vec{\mathbf{x}}_j) \\ &= (\vec{\mathbf{q}} \oplus \vec{\mathbf{q}}) \oplus (\vec{\mathbf{e}}_i \oplus \vec{\mathbf{e}}_j) \\ &= \vec{\mathbf{0}} \oplus (\vec{\mathbf{e}}_i \oplus \vec{\mathbf{e}}_j) = (\vec{\mathbf{e}}_i \oplus \vec{\mathbf{e}}_j) \end{aligned} \tag{3}$$

The above Eq. (3) shows that the mixed signal received at the reader side is obtained by $\vec{\mathbf{e}}_i \oplus \vec{\mathbf{e}}_j$. Since $\vec{\mathbf{e}}_i$, $\vec{\mathbf{e}}_j$, and $\vec{\mathbf{q}}$



(a) (b) (c)

Fig. 3. Verifying the bit-wise synchronization of ON-OFF keying modulation

are known to the reader, thus the original tag signals $\vec{\mathbf{x}_i}$ and $\vec{\mathbf{x}_j}$ can be recovered as

$$\begin{aligned}\vec{\mathbf{x}_i} &= \vec{\mathbf{y}_R} \oplus \vec{\mathbf{e}_j} \oplus \vec{\mathbf{q}} = (\vec{\mathbf{e}_i} \oplus \vec{\mathbf{e}_j}) \oplus \vec{\mathbf{e}_j} \oplus \vec{\mathbf{q}} \\ &= \vec{\mathbf{e}_i} \oplus (\vec{\mathbf{e}_j} \oplus \vec{\mathbf{e}_j}) \oplus \vec{\mathbf{q}} = \vec{\mathbf{e}_i} \oplus \left(\vec{0}\right) \oplus \vec{\mathbf{q}} \\ &= \vec{\mathbf{e}_i} \oplus \vec{\mathbf{q}}\end{aligned} \tag{4}$$

$$\begin{aligned}\vec{\mathbf{x}_j} &= \vec{\mathbf{y}_R} \oplus \vec{\mathbf{e}_i} \oplus \vec{\mathbf{q}} = (\vec{\mathbf{e}_i} \oplus \vec{\mathbf{e}_j}) \oplus \vec{\mathbf{e}_i} \oplus \vec{\mathbf{q}} \\ &= \vec{\mathbf{e}_j} \oplus (\vec{\mathbf{e}_i} \oplus \vec{\mathbf{e}_i}) \oplus \vec{\mathbf{q}} = \vec{\mathbf{e}_j} \oplus \left(\vec{0}\right) \oplus \vec{\mathbf{q}} \\ &= \vec{\mathbf{e}_j} \oplus \vec{\mathbf{q}}\end{aligned} \tag{5}$$

Similarly, this proof process can be easily extended to the case where the number of responding tags is 3, 4, ..., m. Therefore, Theorem 1 is yielded. □

Theorem 1 shows that as long as the tags respond according to the designed characteristic code and group, the reader can identify more than one tag in a same slot. Thus, RFID system can potentially improve the reading performance. The challenge lies in how to group potential tag IDs and decide what query prefixes should be used to probe tags.

Group query: After dividing all potential tag IDs into several characteristic groups, a special query is needed to probe the tags belonging to an individual group. According to the above mentioned rule that all of IDs in each group only have one bit different from the query (named group query), we need to find out all potential group queries. We define this problem as group query allocation problem. We will elaborately introduce the group query allocation method in the following section.

Generally, we denote a K dimensional binary vector space $\{0,\ 1\}^K$, where each element (with each bit represented as 0 or 1) is a row vector in this space. The $\{0,\ 1\}^K$ can be divided into M groups. These M groups need to meet the following three principles.

Principle 1 (Disjointness): $\forall G_i,\ G_j \in \{0,\ 1\}^K,\ i \neq j$ should satisfy

$$G_i \cap G_j = \emptyset \tag{6}$$

where G_i and G_j represent i-th and j-th groups of binary vectors with K-dimension.

Principle 2 (Differentiability): $\forall G_i,\ \exists \vec{\mathbf{g}_i} \in \{0,\ 1\}^K$, there is

$$\left\|\left(\vec{\mathbf{Q}_i} \oplus \vec{\mathbf{g}_i}\right)\right\| = 1,\ \forall \vec{\mathbf{g}_i} \in G_i \tag{7}$$

where $\vec{\mathbf{Q}_i} = \& G_i$ and $\vec{\mathbf{g}_i}$ is a binary vector belonging to G_i. The total number of group queries is M. Let $\mathbb{Q}$ to denote the set of all group queries, i.e., $\vec{\mathbf{Q}_i} \in \mathbb{Q}\,(i = 1,\ 2,\ ...,\ M)$.

Principle 3 (Completeness): when grouping is complete, all individual groups can form the entire vector space, i.e.,

$$G_1 \cup G_2 \cdots \cup G_M \equiv \{0,\ 1\}^K \tag{8}$$

The above Principles 1 and 3 indicate that the entire vector space can be partitioned into mutually disjoint groups. Principle 2 shows that each characteristic group has a corresponding group query, which is different from each row vector of the group by only one bit. For a given group query, it is straightforward to obtain all row vectors associated to the group query. The essence of group query allocation problem is to find out all group queries in $\mathbb{Q}$. Then, we can make the following summarizations. If a vector space with dimension of K is to be partitioned into $2^K/K$ groups according to the above three principles, K must be an positive integer power of 2. Each characteristic group associated to the group query owns K row vector elements which can be viewed as tag IDs, and the group query is not included in the group. Any two characteristic groups are mutually disjoint.

4 THE PROPOSED SEGMENT DETECTION BASED CHARACTERISTIC GROUP QUERY TREE (SD-CGQT) APPROACH

4.1 Group query allocation method

According to the previous description, we know that an important challenge of SD-CGQT protocol is the group query allocation problem. Only by dividing the tag ID set into several characteristic groups and then allowing each group of tags to respond to the corresponding group query, the SD-CGQT protocol can significantly improve the reading performance. So, it requires a solution to find out all potential group queries and associated characteristic groups. Based on the above principles, we can make some propositions which are used to find out a solution for group query allocation problem. The propositions are given as follows.

Proposition 1. *In group query allocation problem, each characteristic group corresponds to a unique group query. For* $\forall\vec{\mathbf{Q}}_i = \&G_i$ *and* $\forall\vec{\mathbf{Q}}_j = \&G_j\ (i \neq j)$*, no common vector* $\vec{\boldsymbol{x}} \in \{0,\ 1\}^K$ *satisfies the following formula.*

$$\left\|\vec{\boldsymbol{x}} \oplus \vec{\mathbf{Q}}_i\right\| = 1,\ \left\|\vec{\boldsymbol{x}} \oplus \vec{\mathbf{Q}}_j\right\| = 1 \tag{9}$$

Proof: We can use reduction to absurdity to prove Proposition 1. Suppose there is a vector $\vec{\mathbf{x}}$ that associates with two group queries, i.e., the Eq. (9) is satisfied. Then we have $\vec{\mathbf{x}} \in G_i \cap G_j\ (i \neq j)$. Thus, we can get

$$G_i \cap G_j \neq \emptyset\ \ (i \neq j) \tag{10}$$

The above formula obviously conflicts with Principle 1, so we conclude that the assumption is not valid, and Proposition 1 is proved. □

Proposition 2. *In group query allocation problem, the entire vector space* $\{0,\ 1\}^K$ *can be divided into* $2^K/K$ *disjoint groups and each group contains* K *vectors.*

Proof: For a given group query $\vec{\mathbf{Q}}_i$, it is a vector with K-dimension, i.e.,

$$\left|\vec{\mathbf{Q}}_i\right| = K \tag{11}$$

Based on Theorem 1 and Principle 2, we can have

$$\vec{\mathbf{e}_x} \oplus \vec{\mathbf{Q}}_i = \vec{\mathbf{g}_i} \in G_i\ (x = 1,\ 2, ...,\ K) \tag{12}$$

So we know that G_i contains K vectors. Since the entire vector space owns 2^K vectors, the number of groups should be $2^K/K$. So, Proposition 2 can be yielded [1]. □

Proposition 3. *If* $\vec{\mathbf{Q}}_i = \&G_i$*, then there is only one other group query* $\vec{\mathbf{Q}}_j = \&G_j\ (i \neq j)$ *satisfies* $\left\|\vec{\mathbf{Q}}_i \oplus \vec{\mathbf{Q}}_j\right\| = 1$ *where* $\vec{\mathbf{Q}}_i$ *can be viewed as a conjugate group query of* $\vec{\mathbf{Q}}_j$*.*

Proof: According to Proposition 2, we know an arbitrary group query $\forall\vec{\mathbf{Q}}_i \in \{0,\ 1\}^K\ (i = 1,\ 2, ...,\ 2^k/K)$ is also a vector element of another group. Thus, there exists a group G_j contains $\vec{\mathbf{Q}}_i$, i.e.,

$$\vec{\mathbf{Q}}_i \in G_j\ \ (i \neq j) \tag{13}$$

According to Principle 2, we have

$$\left\|\vec{\mathbf{Q}}_i \oplus \vec{\mathbf{Q}}_j\right\| = 1 \tag{14}$$

From Eq. (14), we know that there is at least one conjugate group query for an arbitrary group query. We assume that in addition to $\vec{\mathbf{Q}}_j$, there is another conjugate group query $\vec{\mathbf{Q}}_k (i \neq j \neq k)$ for $\vec{\mathbf{Q}}_i$. Based on Principle 2, we have

$$\left\|\vec{\mathbf{Q}}_i \oplus \vec{\mathbf{Q}}_j\right\| = 1,\ \left\|\vec{\mathbf{Q}}_i \oplus \vec{\mathbf{Q}}_k\right\| = 1,\ i \neq j \neq k \tag{15}$$

Since $\vec{\mathbf{Q}}_j = \&G_j$ and $\vec{\mathbf{Q}}_k = \&G_k$, there is

$$\begin{aligned} &\vec{\mathbf{Q}}_i \in G_j \cap G_k \\ &\Rightarrow G_j \cap G_k \neq \emptyset \end{aligned} \tag{16}$$

The formula (16) obviously conflicts with Principle 1, so we know that the assumption is not valid and Proposition 3 is proved. □

Proposition 4. *For arbitrary two group queries* $\vec{\mathbf{Q}}_i$ *and* $\vec{\mathbf{Q}}_j$ $(i \neq j)$*, if* $\left\|\vec{\mathbf{Q}}_i \oplus \vec{\mathbf{Q}}_j\right\| \neq 1$*, they must satisfy*

$$\left\|\vec{\mathbf{Q}}_i \oplus \vec{\mathbf{Q}}_j\right\| \geq 3 \tag{17}$$

Proof: We still use reduction to absurdity to prove it. Suppose there are arbitrary two group queries $\vec{\mathbf{Q}}_i$ and $\vec{\mathbf{Q}}_j$ $(i \neq j)$ satisfying

$$\left\|\vec{\mathbf{Q}}_i \oplus \vec{\mathbf{Q}}_j\right\| = 2 \tag{18}$$

We also can find out arbitrary two unit vector $\vec{\mathbf{e}_x}$ and $\vec{\mathbf{e}_y}$ $(x \neq y)$, satisfying

$$\vec{\mathbf{Q}}_i \oplus \vec{\mathbf{Q}}_j = \vec{\mathbf{e}_x} \oplus \vec{\mathbf{e}_y} \tag{19}$$

The Eq. (19) can be further expressed as

$$\vec{\mathbf{Q}}_i \oplus \vec{\mathbf{e}_x} = \vec{\mathbf{Q}}_j \oplus \vec{\mathbf{e}_y} \tag{20}$$

Let $A = \vec{\mathbf{Q}}_i \oplus \vec{\mathbf{e}_x}$ and $B = \vec{\mathbf{Q}}_j \oplus \vec{\mathbf{e}_y}$, we have

$$A = B\ (A \in G_i,\ B \in G_j) \tag{21}$$

Thus, we can have

$$G_i \cap G_j = A = B \neq \emptyset\ \ (i \neq j) \tag{22}$$

The formula (22) obviously conflicts with Principle 1, so the assumption is not valid and Proposition 4 can be proved. □

Proposition 4 indicates that two non-conjugated group queries are geometrically faraway from each other with a minimal Hamming distance of 3. Intuitively, Theorem 1 provides a theoretical basis for SD-CGQT protocol, and four Propositions provide the basis for the design of group query allocation method. Specifically, based on Propositions, a solution to group query allocation method (GQAM) is described in Algorithm 1.

Algorithm 1 *A Solution to Group Query Allocation Method*

```
Input: $\mathbb{Q}_{ini} = \emptyset$ and $S^K = \{0,\ 1\}^K$
```

---

[1] It is noted that the performance of SD-CGQT is affected by the values of K. When the value of K is larger, the number of tags that the reader can successfully identify in a time slot will be increased. At the same time, there will be many disjoint groups in the entire tag set. The performance advantage is less pronounced when the number of tags is relatively small. The performance benefit becomes more pronounced as the number of tags increases. Considering the sparsity of the tag ID distribution in the actual system, it is not necessary to set the K value too large.

```
**Output:** $\mathbb{Q}_{out}$
Randomly pick up a row vector $\vec{\boldsymbol{\alpha}}_0$ from $S^K$
Pick up a vector $\vec{\boldsymbol{\alpha}}_1$ from $S^K$ that satisfies $\|\vec{\boldsymbol{\alpha}}_1 \oplus \vec{\boldsymbol{\alpha}}_0\| = 1$
Push $\vec{\boldsymbol{\alpha}}_0$ and $\vec{\boldsymbol{\alpha}}_1$ into $\mathbb{Q}_{ini}$ and pop out them from $S^K$
**while** ($|\mathbb{Q}_{ini}| \le \frac{2^K}{K}$) do
    Pick up a vector $\vec{\boldsymbol{\beta}}_0$ from $S^K$ that satisfies
    $\left\|\vec{\boldsymbol{\beta}}_0 \oplus \vec{\mathbf{Q}}_i\right\| \ge 3,\ \forall \vec{\mathbf{Q}}_i \in \mathbb{Q}_{ini}$
    From $S^K$ pick up a vector that satisfies $\left\|\vec{\boldsymbol{\beta}}_1 \oplus \vec{\boldsymbol{\beta}}_0\right\| = 1$
    Push $\vec{\boldsymbol{\beta}}_0$ and $\vec{\boldsymbol{\beta}}_1$ into $\mathbb{Q}_{ini}$, and pop out them from $S^K$
**end while**
$\mathbb{Q}_{out} = \mathbb{Q}_{ini}$
```

TABLE 2
AN EXAMPLE FOR $K = 4$ BY USING THE PROPOSED GROUP QUERY ALLOCATION METHOD

Group query	Characteristic group
$\vec{\mathbf{Q}}_1 = 0000$	$G_1 = \{1000,\ 0100,\ 0010,\ 0001\}$
$\vec{\mathbf{Q}}_2 = 0001$	$G_2 = \{1001,\ 0101,\ 0011,\ 0000\}$
$\vec{\mathbf{Q}}_3 = 1110$	$G_3 = \{0110,\ 1010,\ 1100,\ 1111\}$
$\vec{\mathbf{Q}}_4 = 1111$	$G_4 = \{0111,\ 1110,\ 1101,\ 1011\}$

It is noted that GQAM has multiple possible solutions. For different initial parameters, we can obtain different solutions. Tab. II gives one set of possible solutions for $K = 4$. As observed in the Tab. II, each group query is associated with a characteristic group. When some tags from a same group respond simultaneously, the reader can resolve the original ID information using collided signals.

4.2 SD-CGQT: Algorithm Description

According to the description above, group queries and characteristic groups can be potentially used to recover the collided signals when multiple tags respond to the reader at the same time. However, the length of a group query is limited to an integer power of 2. Considering that the ID length of the tag in many scenarios is not strictly equal to the length of group query, a segment detection based characteristic group query tree (SD-CGQT) can be designed to accelerate the tag identification in conventional scenarios. The process design of the entire algorithm is based on the idea in section 1.3 and solutions in section 1.4. The detailed flowchart of SD-CGQT is illustrated in Fig. 4.

Similar to previous work, the reader also maintains a stack to store the prefix parameters in SD-CGQT. The communication mechanism of SD-CGQT and the other algorithms are the same. The tag responds to the reader through its own matching circuit. As concluded in previous work, the prefix matching method consumes low energy and less the tag reaction time [35]. At the beginning of identification process of SD-CGQT, the reader broadcasts a probe command with parameters (F_{pre}, flag, s_{pre}) to probe tags. F_{pre} can be seen as a slot prefix, the tags with IDs matching to F_{pre} will respond in the slot. flag refers to the flag bit of the reader commands, which determines what action the reader will take after receiving the tag response. Specifically, the value of flag can be either 0 or 1. s_{pre} can be seen as a sub-slot prefix, the tags with IDs matching to it will respond in the sub-slot. The probe command could be Query, QueryR, QueryG or QueryRep. Each command contains only one F_{pre} and multiple s_{pre}. In the proposed SD-CGQT protocol, the reader introduces segment detection and partial collision recovery mechanism (the reader uses characteristic group to recover the collided strings). After receiving the responding binary string from tags, the reader decodes it and locates the collision through segment detection, where a segment is a K bits binary string.

- **Prefix matching and responding at the tag side**: After receiving the probe command from the reader, the involved tags extract command parameters and execute the corresponding operations.
    1) The tag first matches F_{pre} with its ID, and if matched, it will return the data according to the value of $flag$, s_{pre} and command type.
    2) If $flag = 0$, the tag uses upper K bits (called a segment, an arbitrary segment is denoted as W_i) of its remaining ID to match s_{pre}. If matched, the tag replies the remaining ID, otherwise it waits for the next query. If $flag = 1$, the tag maps the corresponding collided bits of s_{pre} into an $M = 2^m$ (if $1 < m < K$) bits string and returns it to the reader where m means the number of collided bits in s_{pre}. The detailed mapping function refers to our previous work [30]. If $m = K$, the tag compares its current segment with each group query and generates a 2^K bits string (The string SG can be expressed in sections as $\vec{\mathbf{g}}_1, \vec{\mathbf{g}}_2 \cdots \vec{\mathbf{g}}_{\frac{2^K}{K}}$). $\vec{\mathbf{g}}_i$ is a K-bits string generated by the segment and i-th group query. If the segment belongs to i-th characteristic group, the tag performs $\vec{\mathbf{g}}_i = \vec{\mathbf{Q}}_i \oplus W_i$ and let the rest part of SG be zeros. For example, suppose the current segment W_i is “1010” which belongs to the 3rd characteristic group as described in Tab. II, the $\vec{\mathbf{g}}_3$=“0100” and the ultimate responding string SG=“0000 0000 **0100** 0000”.
- **New prefix updating and command generating at the reader side**: After receiving the responding string, the reader updates the new prefixes according to the value of type and collided bits.
    1) If $flag = 0$, the reader first updates F_{pre} to $F_{pre} \| s_{pre}$. Then, the reader decodes the receiving segment. If no collision is detected in a W_i, the reader updates F_{pre} to $F_{pre} \| W_i$ and generates a $Query$ command. If a single collided bit is detected in a W_i, the reader terminates the slot and replaces the collided bit with 0 and 1 to obtain W_{i0} and W_{i1}, respectively. For example, when $K = 4$ and W_i is “01x1”, the reader can obtain W_{i0}=“0101” and W_{i1}=“0111”. Then the reader appends W_{i0} and W_{i1} to F_{pre} to update a new F_{pre}s. If the length of F_{pre}s is equal to that of a tag ID, the reader can successfully obtain the corresponding tag IDs. Otherwise, the reader pushes them into the stack used for the following queries. If more than one collided

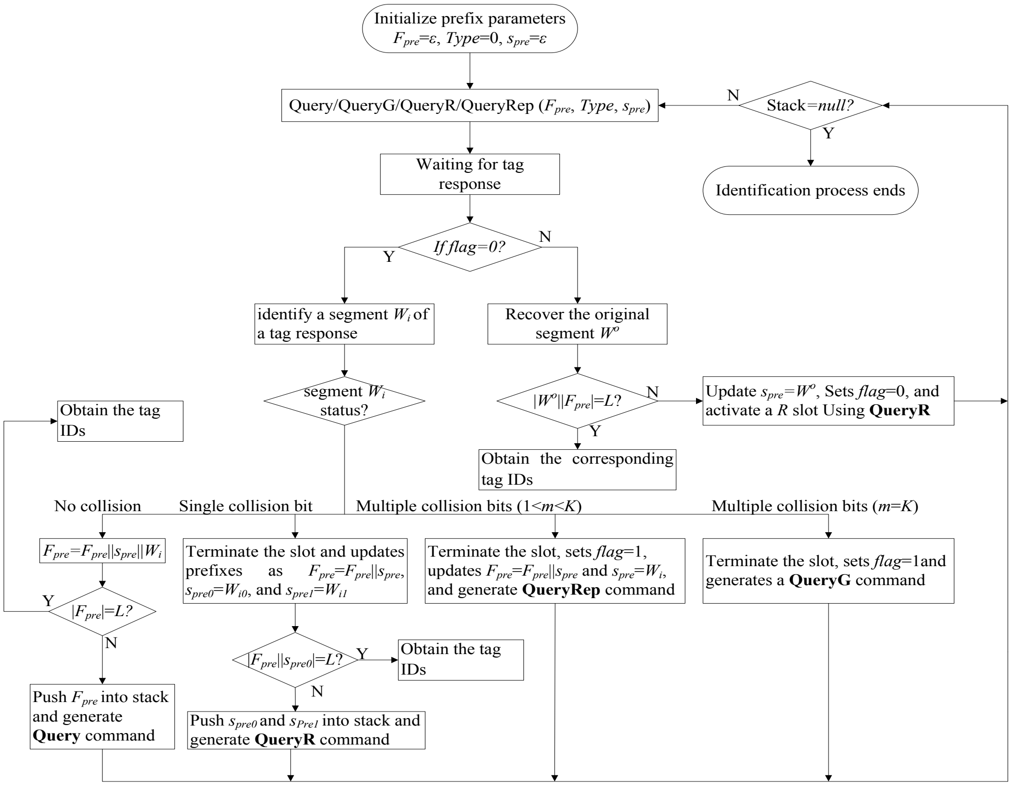


Fig. 4. The flowchart of the proposed SD-CGQT

TABLE 3
THE IDENTIFICATION PROCEDURE FOR AN EXAMPLE OF SD-CGQT

slot	Probe command	Response				Identification
<1>	Query (ε, 0, ε)	x01x				
<2>	QueryRep (ε, 1, x01x)	0xxx				
<3>	QueryR (ε, 0, 0010, 0011, 1010)	011x	1010		xxxx	Tags B, C, and A are identified
<4>	QueryG (ε, 1, 1010)	0000	x000	x0x0	0x00	Tags G, E, F, and D are identified

bits are detected in the W_i ($1 < m < K$), the reader terminates the slot, sets $flag = 1$, records the collided position and updates s_{pre} as $W_i \| F_{pre}$, and generates a $QueryRep$ command. If $m = K$, the reader sets $flag = 1$, terminates the slot and generates a group query command $QueryG$ to allow the tags to respond a 2^K bits string namely SG.

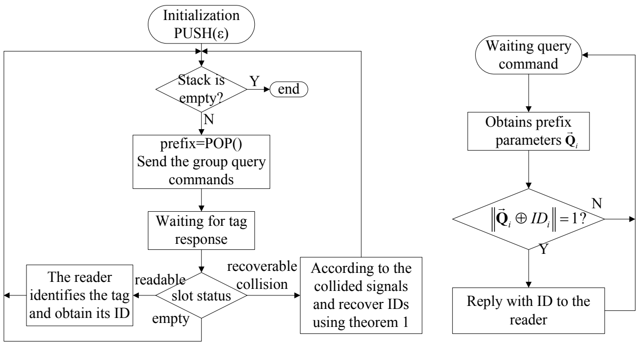
2) If $flag = 1$, the reader recovers the original segment W^Os using the mapped string from tags and recorded collision information in s_{pre} and judges whether the length of $W^O \| F_{pre}$ equals to that of a tag ID. If so, the reader can obtain the corresponding tag IDs. Otherwise, the reader updates s_{pre} as W^O, sets $flag = 0$ and generates a $QueryR$ command to activate a R slot. Where R is the number of recovered segments. In R slot, there are R s_{pre}s that allow various tags to match and respond in sequence.

The reader continues to probes tags until the prefix stack is empty. As shown in Tab. III, an example of using the SD-CGQT protocol to identify seven tags is described, where the tag IDs are “00111010”, “00100110”, “00100111”, “10101011”, “10101100”, “10100110”, and “10101001”, respectively. In slot <1>, the reader transmits a Query (ε, 0, ε) to start the identification process. All tags match the prefix parameters and respond to the reader with their remaining IDs. The reader identifies the received string segment by segment, it terminates the slot and sets $flag = 1$ because a collision is detected. In slot <2>, the reader issues a QueryRep command to allow the tags to reply the mapped strings. After receiving the collided string “0xxx”, the reader recovers the original segments are “0010”, “0011”, and “1010”, respectively. In slot <3>, the reader issues a QueryR command to start a R slot to allow various tags to respond in sequence. The tags B and C match the s_{pre1} and reply “0110” and “0111”, respectively. After receiving the collided string “011x”, the reader can identify tags B and C because there is only one collided bit and each tag owns an unique ID. Similarly, the tag A matches the s_{pre2} and replies “1010”, thus the reader can identify it. Since four tags match the s_{pre3}, the reader will generate QueryG command to probe them. The tags D, E, F, and G match the s_{pre}

and respond simultaneously. After receiving the collided string "0000 x000 x0x0 0x00", the reader can determine which characteristic group each segment belongs to, and then accurately decode them using group query allocation method described in Section III. A. For example, since the 2nd segment is "x000", the reader can perform $0001 \oplus \vec{\mathbf{e}}_1$ to recover the original segment of "1001". Similarly, the reader can recover the original segments of "0110","1100", and "1011", respectively. Therefore, in slot <4>, the reader can successfully identify tags G, E, F, and D.

4.3 SD-CGQT For Scenario A

Although the proposed SD-CGQT is presented for conventional scenarios, it also can be simplified for some special scenarios with relative few tags using short tag IDs (such as 8 bits[2]). For example, one typical application is the check-in system of with about 200 visitors, where each visitor carries a 8-bit tag. We name such scenario as scenario A. Assume that each tag ID is a binary string with length of L which is regarded as a row vector in the vector space of $\{0,\ 1\}^L$. The SD-CGQT is simplified for the scenario A that the length of query prefix is equal to the length of tag ID, i.e., $L = K$. The workflow of the SD-CGQT for scenario A (SD-CGQT-A) is similar to conventional QT-based protocol except for the core query-response mechanism. Fig. 5 illustrates the flowchart of the proposed SD-CGQT-A protocol. From Fig. 5, we know that the implementation process of SD-CGQT-A is very straightforward and intuitive. Compared to other prior arts [27-29], neither reader nor tags require additional memory or overhead (such as counter, random number generator, etc.).



(a) (b)

Fig. 5. The flowchart of SD-CGQT for scenario A (SD-CGQT-A): (a) for reader (b) for tags

TABLE 4
THE IDENTIFICATION PROCEDURE FOR AN EXAMPLE OF CGQT

Slot	Command	Response	Identification
<1>	QueryG (0000)	xxx0	Tags A, B, and C are identified
<2>	QueryG (0001)	xxx1	Tags D, E, and F are identified
<3>	QueryG (1110)	empty	No tag is identified
<4>	QueryG (1111)	1110	Tag G is identified

The SD-CGQT-A protocol is applied to the identification example of seven tags whose IDs are "0010", "0100", "1000", "0101", "0011", "1001", and "1110". The communication procedure is described in Tab. IV. The reader starts each slot by sending a group query popped out from the stack. In slot <1>, the reader sends group query of "0000" to probe tags, tags A, B, and C respond. After receiving the mixed signal "xxx0", the reader can recognize the 1st, 2nd, and 3rd bits are collided. According to the principle of SD-CGQT-A, the reader performs $(0000 \oplus \vec{\mathbf{e}}_1)$=1000, $(0000 \oplus \vec{\mathbf{e}}_2)$=0100, and $(0000 \oplus \vec{\mathbf{e}}_3)$=0001, respectively. Thus, the reader can identify Tags C, B, and A. Similarly, the reader can identify Tags F, D, and E in slot <2> by performing $(0001 \oplus \vec{\mathbf{e}}_1)$=1001, $(0001 \oplus \vec{\mathbf{e}}_2)$=0101, and $(0001 \oplus \vec{\mathbf{e}}_3)$=0011, respectively. In slot <3>, no tags match the group query of "1110", thus the reader detects an empty slot. The reader transmits group query of "1111" to probe tags in slot <4>, only tag G responds, so it can be identified directly.

It can be observed from Tab. IV, the SD-CGQT-A protocol spends only four queries to complete the successful identification of seven tags. Thus, it has significant advantages in the number of queries and communication complexity while simplifying the workflow of SD-CGQT.

5 SIMULATION RESULTS

5.1 Simulation Setup

In this section, we evaluate the performance of the proposed solutions through a series of Monte Carlo [34] experiments and compare their results with prior arts including CT [25], CwT [29], MQT [27], MCT [28] and STT [18]. We setup high dense network scenarios with a single reader and a variety of tags by MATLAB 2012b. Same as in [10-15][26-30], the wireless channel between the reader and tags are assumed as no error-prone[3]. Referring to the existing literatures [20][28-30], the parameters used in MATLAB simulations are summarized in Tab. V. L is the length of a tag ID. T_1 is the time required for tag to generate a response after each reader command. T_2 is the time required for the reader to process the received tag response. T_3 is the guard time between two consecutive tag responses. Compared with the previous algorithms, the SD-CGQT only adds a few more parameters in reader commands. However, we have included the increased command length brought by the proposed SD-CGQT in our simulations. Therefore, the comparison of the experimental results is fair. In our simulations, to reduce the randomness and ensure the convergence, the simulation results are average over 1000 iterations.

5.2 Results on Experimental Scenario 1 in Numerous Metrics

1) System efficiency: In the existing work, system efficiency is an important metric to evaluate the performance of

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[2] It is noted that according to specification of RFID standards the tag ID length should be a multiple of 8. Therefore, we do not consider the other scenarios that the tag ID length is equal to other values.

[3] In essence, an RFID anti-collision protocol is a kind of MAC protocol. So, it is unable to directly eliminate or suppress noise. Noise affects all anti-collision algorithms. In the RFID system, the reader suppresses the noise through its own receiver. When the power of the noise is higher than the sensitivity threshold of the receiver, the reader cannot correctly recover the signal.

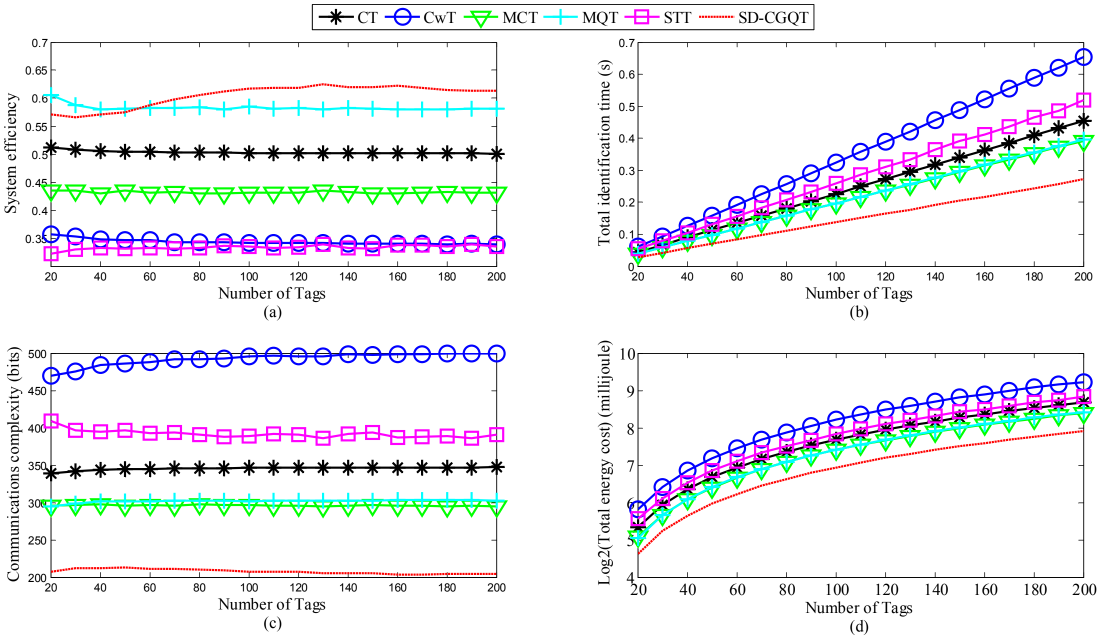


Fig. 6. Comparison of various protocols in experimental scenario 1: (a) system efficiency (b) total identification time (c) communication complexity (d) total energy cost

TABLE 5
THE PARAMETERS USED IN MATLAB SIMULATIONS

Experimental scenarios	1	2
n	20∼200	200∼2000
L	96 bits	96 bits
Data rate	160 kbps	160 kbps
T_1	25 µs	25 µs
T_2	25 µs	25 µs
T_3	30 µs	30 µs
P_{tx}	825 mw	825 mw
P_{rx}	125 mw	125 mw
The number of simulations	1000	1000

RFID collision arbitration protocol, which is defined as the number of identified tags divided by the number of total slots required to identify these tags. *The SD-CGQT is superior to other protocols and improves the system efficiency of the best reference QT-based protocol by average of 3.65% in experimental scenario 1.* Fig. 6 (a) compares the system efficiency of all comparative approaches when the number of tags is from 20 to 200 with $L = 96$. Observed in Fig. 6 (a), SD-CGQT achieves an improvement in system efficiency and the system efficiency increases as the number of tags n increases. The reason is that compared with other solutions, the SD-CGQT can resolve partial ID strings in a collided slot using characteristic code and segment detection mechanism. As the tag cardinality grows, the number of partial ID strings can be resolved in the collision slot will also increase, therefore, the system efficiency is greatly improved.

2) Total identification time: The total identification time is defined as the cumulative time required to identify all tags. Such metric can well eliminate the impact of the discrepancy in slot length between comparative protocols on the whole identification performance. *The SD-CGQT reduces the total identification time of the best reference QT-based protocol by an average of 30.3% in experimental scenario 1.* Fig. 6 (b) depicts the total time consumed by various protocols when the number of tags varies from 20 to 200 with $L = 96$. Observed in Fig. 6 (b), SD-CGQT requires the least time identify the same cardinality size of tags compared to comparative methods. We can also observe that various protocols exhibit diverse ranks under different evaluation metrics. For example, the number of total slots of MQT is less than that of MCT, however, its total identification time is longer than MCT. The reason is that the total identification time is determined by the number of slots and the slot length. Although MQT consumes fewer slots than MCT, it requires more time to identify the tags because the mapped arbitration string and ID string need to transmitted together in a slot. Benefiting from the characteristic group and segment detection mechanism, the reader can reduce the collision arbitration time and hence shorten the total identification time.

3) Communication complexity and energy cost: The communication complexity is defined as the average amount (measured in number of bits) of messages per tag identification transmitted by the reader and tags during tag identification process, which is positively related to the time and energy consumption in tag identification process [13, 19-20, 28-29]. *The SD-CGQT reduces the average amount of messages per tag identification of the best reference QT-based protocol by an average of 30% in experimental scenario 1.* Fig. 6 (c) demonstrates the communication complexity of all comparative protocols. As can be observed, various protocols do not maintain the same performance ranking with different evaluation metrics. For example, although the number of total slots consumed by MCT is more than CT and CwT, its communication complexity is lower than them. The main

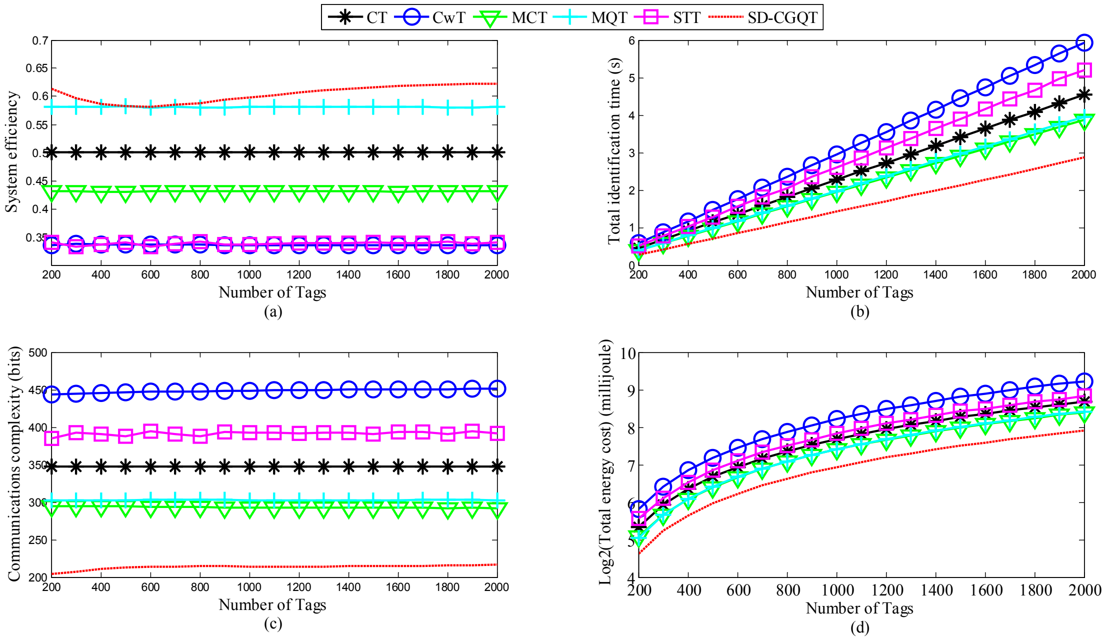


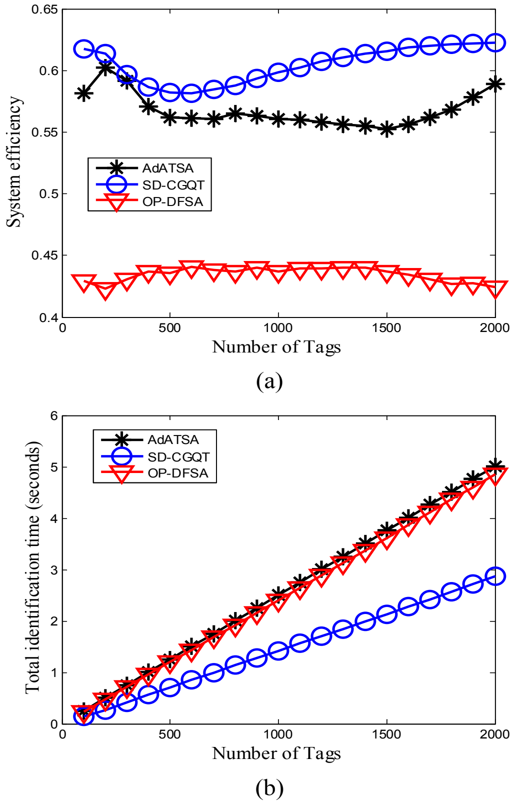
Fig. 7. Comparison of various protocols in experimental scenario 2: (a) system efficiency (b) number of total slots (c) communication complexity (d) total energy cost

reason is that in MCT most of slots are trigged by short command, thereby the total number of transmitted bits is significantly reduced. Compared to other approaches, SD-CGQT protocol reduces the total number of queries while limiting the amount of data transmission in collision slot through segment detection mechanism, so it can greatly reduce the communication complexity. *The proposed SD-CGQT saves the total energy cost in tag identification process of the best reference QT-based protocol by an average of 27.9% in experimental scenario 1.* Fig. 6 (d) illustrates the total energy cost of all comparative protocols. It also verify that SD-CGQT outperforms the other reference protocols in terms of energy consumption. The reason is that the SD-CGQT protocol limits the amount of data transmission while reducing the total number of slots.

5.3 Results on Experimental Scenario 2 in Numerous Metrics

The simulation results in experimental scenario 1 show that the SD-CGQT performs an unparalleled performance advantages when the tag cardinality is relatively small. In practical applications, there are many scenarios with dense tags. Hence, we further investigate the performance of the SD-CGQT protocol under experimental scenario 2.

1) System efficiency: *The SD-CGQT is superior to all comparative solutions and improves the system efficiency of the best reference QT-based protocol by average of 3.94% in experimental scenario 2.* Fig. 7 (a) compares the system efficiency of various approaches when the number of tags is between 200 to 2000 with $L = 96$. The similar performance ranking as shown in Fig. 7 (a) can also be observed in Fig. 7 (a). The experimental results further indicate that the performance of QT-based approaches is hardly affected by the tag cardinality. The reason is that the QT-based protocol does not need to estimate the number of remaining tags in tag identification process.



(a)

(b)

Fig. 8. Comparison of SD-CGQT and other Aloha-variant protocols: (a) system efficiency (b) total identification time

2) Total identification time: *The SD-CGQT is superior to all comparative solutions and reduces the total identification time*

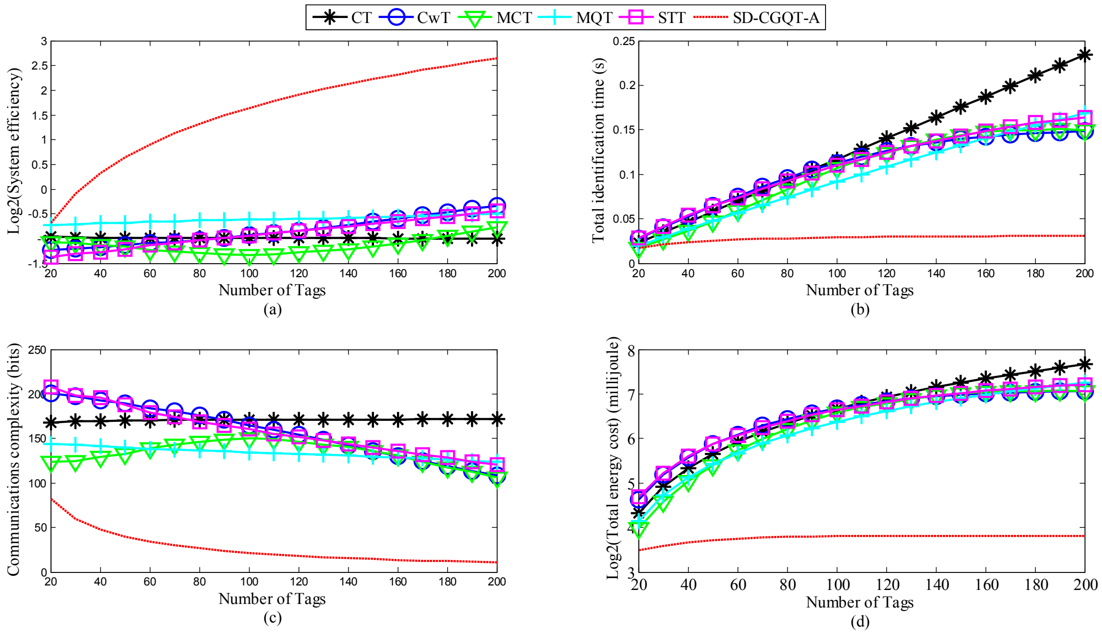


Fig. 9. Comparison of various protocols in special scenario: (a) system efficiency (b) number of total slots (c) communication complexity (d) total energy cost

of the best reference QT-based protocol by average of 27.3% in experimental scenario 2. Fig. 7 (b) compares the cumulative time required to identify all tags of various approaches when the number of tags is between 200 to 2000 with $L = 96$. The same performance ranking as shown in Fig. 7 (a) can be observed in Fig. 7 (b). Although MCT can use multi-bit collision arbitration to split the collided tag set into several subsets, it is unable to eliminate the empty queries in tag identification process which increases the coordination time, especially when the number of tags is large. Although the SD-CGQT protocol does not significantly reduce the number of slots compared to MQT, it effectively reduces the number of transmitted bits in collision slots, thereby greatly shortening the total identification time.

3) Communication complexity and energy cost: *The SD-CGQT reduces the average amount of messages per tag identification of the best reference QT-based protocol by an average of 27.3% in experimental scenario 2.* Fig. 7 (c) demonstrates the communication complexity of all comparative protocols. As illustrated in Fig. 7 (c), the communication complexity of all protocols is independent of the number of tags. In other words, the communication complexity is only related to the length of tag ID and command. Since the CwT attempts to limit the number of transmitted bits in each slot by introducing window technology, it requires more slots to identify the same batch of tags, which dramatically improve the average amount of messages per tag identification. *The SD-CGQT saves the total energy cost of the best reference QT-based protocol by an average of 27.9%.* Fig. 7 (d) compares the total energy cost for identifying all tags. As described above, the communication complexity implicitly represents the energy cost during the communication process. Thus, a similar performance ranking can be observed in Fig. 7 (d). It also shows evidence that SD-CGQT is significantly better than the other comparative protocols in terms of energy consumption.

The above results are compared with the QT-based algorithms because the performance of the current Aloha-based algorithms are generally worse than that of the QT-based algorithms. To more comprehensively demonstrate the performance of our proposed SD-CGQT algorithm, we compare it with two representatives of Aloha-variant algorithm including optimal partition based dynamic framed slotted Aloha (OP-DFSA)[36] and adaptive assigned tree slotted Aloha (AdATSA)[37]. Fig. 8 compares the system efficiency and total identification time for identifying all tags. The experimental results in Fig. (8) show the proposed SD-CGQT still outperforms other solutions.

5.4 Results on special scenario in Numerous Metrics

Both simulation results in experimental scenario 1 and 2 verify the effectiveness of SD-CGQT when the tag ID length is long. However, in many scenarios, the tag ID length maybe very short such as 8 bits. The SD-CGQT protocol is simplified into SD-CGQT-A to cope with the tag identification in such special scenarios with short IDs. Therefore, we need to further evaluate the performance of SD-CGQT-A.

The SD-CGQT-A is superior to all comparative solutions and improves the system efficiency of the best reference QT-based protocol by average of 4.24 times when the tag ID is short. Fig. 9 (a) compares the system efficiency of various protocols when the number of tags is between 20 to 200 with $L = 8$. Observed in Fig. 8 (a), SD-CGQT-A shows an unparalleled advantages in system efficiency, and its system efficiency increases dramatically as the number of tags n increases. For example, the maximum system efficiency is 6.25 when the number of tags is 200. The reason is as follows. In SD-CGQT-A a tag ID can be served as a vector in a vector space of $\{0,\ 1\}^L$. The SD-CGQT-A can resolve multiple tags simultaneously in a collision slot by using group query and characteristic groups. As the tag population grows, the number of tags can be resolved in the collision slot will also increase, therefore, the system efficiency is greatly improved. According to the principle of SD-CGQT-A, it is expected that as L is a power of 2, the maximum system efficiency is equal to $\frac{n\times L}{2^L}$. The results show that the greater the number of tags to be identified, the higher the system efficiency of SD-CGQT-A.

The SD-CGQT-A reduces the total identification time of the best reference QT-based protocol by average of 71.5% when the tag ID is short. Fig. 9 (b) depicts the cumulative time required to identify all tags of various approaches when the number of tags is between 20 to 200 with $L = 8$. Different from the results observed in Figs. 6 and 7, the SD-CGQT-A achieve a more significant performance improvement. This is mainly attribute to the following reasons. The total identification time is depend on both the number of slots and the slot length. The SD-CGQT-A protocol significantly reduces the total number of slots required in the tag identification process without increasing the slot length. Thus, it greatly shortens the total identification time. In addition, compared to other protocols, the SD-CGQT-A protocol can maintain a constant value in total identification time. In other words, the total identification time required by SD-CGQT-A will not be affected by the number of tags.

The SD-CGQT-A is superior to all comparative solutions and reduces the average amount of messages per tag identification of the best reference QT-based protocol by average of 79.8% when the tag ID is short. Fig. 9 (c) demonstrates the communication complexity of all comparative protocols. Similar to the results in Fig. 9 (a) and Fig. 9 (b), the SD-CGQT-A also makes a significantly improvement over other methods in communication complexity. As also can be found, various approaches do not maintain the same performance ranking with different tag ID length. For example, when $L = 96$ the communication complexity of CT is lower than CwT, however, when $L = 8$ the results is reversed. The reason is that when the tag ID length is long, the CwT protocol consumes more go-on slots, which increases the total amount of transmitted bits in tag identification.

The SD-CGQT-A saves the total energy cost of the best reference QT-based protocol by average of 84.6% when the tag ID is short. Fig. 9 (d) compares the total energy cost for identifying all tags. Similar to Fig. 9 (b) and 9 (c), all protocols performs the same ranking. It also show evidence that SD-CGQT-A outperforms the other comparative protocols in terms of energy consumption. This is because SD-CGQT-A produces fewer number of slots and transmitted messages at both the reader and tags sides.

6 CONCLUSION

In this paper, we have proposed a characteristic group based query tree protocol for fast tag identification, namely SD-CGQT. In SD-CGQT, the tag identification problem is formulated as a partial collision recovery problem and the entire vector space can be divided into mutually disjoint subsets. By introducing partitioning method and group query, vectors from the same subset can respond simultaneously and be successfully identified by the reader with one query. To further cope with the tag identification in some special scenarios, SD-CGQT can be simplified as SD-CGQT-A. By inheriting the features of SD-CGQT, the SD-CGQT-A can achieve an unparalleled improvement over the prior arts. The extensive numerical results have shown that the proposed protocols significantly outperforms all prior QT-based anti-collision protocols for various evaluation metrics especially in total identification time, communication complexity and energy consumption.

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