Research Article

Reader Scheduling for Tag Population Estimation in Multicategory and Multireader RFID Systems

Zhiyong He [ID]

College of Electrical Engineering, Nanjing Vocational University of Industry Technology, Nanjing 210046, China

Correspondence should be addressed to Zhiyong He; 2012100740@niit.edu.cn

Radio Frequency Identification (RFID) technology has been used in numerous applications, e.g., supply chain management and inventory control. This paper focuses on the practically important problem of the rapid estimation of the number of tags in large-scale RFID systems with multiple readers and multicategory RFID tags. RFID readers are often static and have to be deployed strategically after careful planning to cover the entire monitoring area, but reader-to-reader collision (R2Rc) remains a problem. R2Rc decreases the reliability of the estimation of the tag population size, because it results in the failure of communication between the reader and tags. In this paper, we propose a coloring graph-based estimation scheme (CGE), which is the first estimation framework designed for multireader and multicategory RFID systems to determine the distribution of tags in different categories. CGE allows for the use of any estimation protocol to determine the number of tags, prevents R2Rc, and results in higher time efficiency and less power-consumption than the classic scheduling method DCS.

1. Introduction

Radio Frequency Identification (RFID) technology has been widely deployed to monitor objects in the supply chain. Due to a decrease in the price of tags, RFID is increasingly used in many applications, such as real-time inventory control [1–5] and product tracking [6–9]. A simple RFID system consists of a reader, antennas, and a number of tags. The reader sends the continuous waves to tags, which include operation codes and specifying PHY/MAC parameters. When the tag is activated, it will backscatter a message or keep silent according to the reader's command.

Tag estimation is a fundamental functionality for RFID-enabled warehouse management and inventory control. Most tag estimation protocols estimate the population of a single category of tags based on the slot status observed by a single reader. For example, FNEB [1] uses the number of consecutive empty slots to estimate the number of tags. ES [3] exploits the number of singleton slots occupied in a time frame to estimate the tag cardinality. SEM [10] exploits the

Manchester coding mechanism to simultaneously estimate the tag population of multiple categories.

However, the current large-scale RFID systems usually deployed with multiple readers for tracking a large number of tags from multiple categories. Multicategory tag estimation is particularly challenging in multireader RFID systems because of the reader-to-reader collision (R2Rc) and the multicoverage tags. The R2Rc underestimates the tag populations due to the missing reading caused by communication failure, while a multicoverage tag maybe counted multiple times with distinctive readers. Although some reader-scheduling schemes [11–15] were proposed to resolve the issues of R2Rc and multicoverage tags, their time efficiency is far from optimal because none of them makes use of the tag category distribution characteristics. The tag categories are distributed sequentially, and one category tags are centrally piled up together. Hence, they are of low time efficiency because they have to perform the multicategory RFID estimation category by category [4]. It is noted that in large-scale RFID systems, there are another kind of collision types

named tag-to-tag collision. To cope with the tag-to-tag collision, many works [16–20] have been presented. In this paper, we focus on the R2Rc issue.

Therefore, we propose the coloring graph-based estimation (CGE) scheme to reduce the reader-to-reader collisions to improve the time efficiency of tag cardinality estimation schemes in multiple categories and multiple reader RFID systems. Our proposed scheme CGE can discover the interferences among categories, and the categories without interference can be simultaneously estimated. Hence, the time efficiency of our scheme should be much better than others. The scheme uses the distribution of the categories to activate the related readers and eliminates the overlap between the regions of different categories. So, the categories there no overlap between them could estimate the populations simultaneously. Hence, the time efficiency and power consumption of our scheme should be much better than others. The simulation results show that the proposed CGE results in higher time efficiency and less power consumption than the classic scheduling method distributed color selection (DCS) and variable-maximum dstributed color selection (VDCS) [11].

2. The Proposed CGE Protocol

2.1. System Model. A large-scale RFID system commonly has multiple readers and multicategory tags. The tags communicate with the reader by one-hop transmission. Each tag has an identification ID associated with an object. The ID has two parts: the category ID that indicates the type or manufacturer of the associated object and the member ID that represents the sequence number in the category [5]. The tags can be categorized by the system manager according to the manufacturers or brands.

This paper studies the multicategory tag estimation problem in the multireader system. The system consists of a number of RFID tags with λ categories, which are denoted as $C_1, C_2, .. \cdots, C_\lambda$, and μ carefully deployed readers, which are denoted as $R_1, R_2, .. \cdots, R_\mu$. The number of tags in the distinct categories are denoted by $n_1, n_2, .. \cdots, n_\lambda$, respectively. For each category $C_i, i \in [1, \lambda]$, we set a required reliability $\alpha \in (0, 1]$, a confidence interval $\beta \in [0, 1)$, and $P\{| n\hat{}_j - nj |\leq\beta\} \geq \alpha, j \in [1, \lambda]$, where $n\hat{}_j$ is the estimation of n_j. To comply with the C1G2 standard [21], we assume that the system uses the framed slotted Aloha as the MAC layer protocol for resolving tag collisions.

2.2. Detailed Design of CGE. The proposed CGE protocol consists of four stages: category ID collection, coloring of the categorized region, coloring of the categorized readers, and estimation of the population size. These processes provide information on the distribution of the categorized tags, eliminate the overlaps between different category regions, remove the overlaps between readers, and estimate the population size of tags for each category in the monitoring area.

(1) Category ID collection: In a large inventory scenario with a variety of goods (e.g., supermarket), the category IDs of goods are known to reader, but the reset-

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> **Input:** Number of monitoring units: m; Number of colors: M≤m; The relationship matrix between units: X; Initialize the color of regions: Y [0: m−1]=−1; flag=0;
> **Output:** One scheme of graph coloring Y;
>   **Function** UNCOLLISION(int k)
>   **for** each i ∈ [0, k−1) **do**
>   **if** X[k][i] == 1∧Y [k] == Y [i] **then**
>   return false;
>   **e**lse
>   return true;
>   **function** GRAPHCOLOR(int t)
>   p=0;
>   if t>= m **then**
>   flag=1;
>   **while**!flag ∧ p<M **do**
>   Y [t]=p;
>   p=p+1;
>   **if** UNCOLLISION(t) **then**
>   GRAPHCOLOR(t+1);
>   **if** t == 0 **then**
>   return null;
> GRAPHCOLOR(0);

ALGORITHM 1: The coloring region division.

tlement region of each category of goods is unknown to the reader. To make the tag categories free from reader collisions, we need to obtain the spatial distribution region of each category tags. So, one tag at least for one category needs to be single out in an efficient method, and the tag ID should be extracted to represent the distribution of this category. Therefore, in this stage, we leverage the TPS protocol [22] to rapidly collect category information within the communication range of each reader. The TPS need to be executed multiple rounds to collect the category IDs completely, and the process is terminated when there are no more responses in the frame

During the category ID collection stage, we must confirm that there are no overlaps between readers to ensure that the category ID can be collected completely. Since we know the locations of the m readers, we can obtain a $m \times m$ matrix X that represents the collision relationship between the readers. If $X_{ij} = 0$, the readers R_i and R_j have no reader collision and can work simultaneously for collecting category IDs; if $X_{ij} = 1$, the readers R_i and R_j are neighboring readers with overlap regions, and the readers have to operate at different times to avoid a conflict. Given the collision matrix X of readers, the CGE splits the readers into several groups using Algorithm 1. Algorithm 1 is a greedy algorithm. This moment, the monitoring unit is the communication region of one reader, "M" is a variable, and we need to change the value of "M" to obtain a coloring scheme. After reader coloring, the reader nodes with the same color have no overlap region and can be operated simultaneously to collect category IDs. As illustrated in Figure 1(a), there are six readers in the overlap regions. The colored node represents the reader in
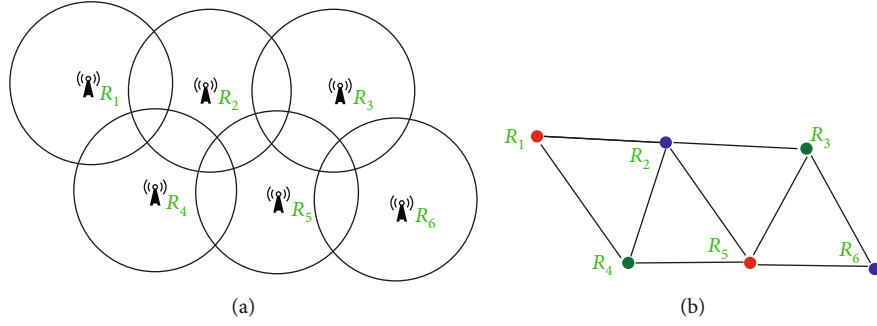
FIGURE 1: An example of reader deployment. (a) Displays a typical RFID system with multireader. (b) A effective batched method in collecting ID phase.
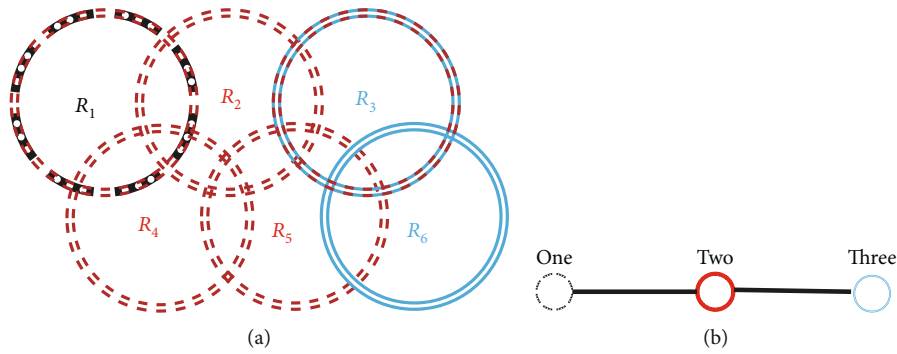

FIGURE 2: Categorized region distribution and the crossing with each other. (a) Categories distribution. (b) The crossing situation of categories distribution regions.

the RFID system, and the line denotes the relationship between the readers. The relationship between the readers is transformed into 8×8 binary matrix, where 0 and 1 represent no connection and a connection, respectively. As shown in Figure 1(b), we divide these readers into three colored batches. R_1 and R_5 will collect the category IDs simultaneously in batch one, R_2 and R_6 will be grouped into batch two, and R_3 and R_4 will in batch three.

(2) Coloring of the categorized region: Each category of tags is monitored by several readers, and we name the monitoring area of these readers categorized region. Due to the population size of each category that is different with each other, the parameters of readers in different categorized region are different, and so we must execute the estimation scheme according to the categorized region

After the first stage, each reader knows the categories within its monitoring region. Subsequently, the distribution region of each category and the relationship between the category nodes are also learned as shown in Figure 2. The category one is monitored by R_1, the category two is monitored by R_1, R_2, R_3, R_4, and R_5, and the category three is monitored by R_3 and R_6. Again, the server runs Algorithm 1 to find the groups of categories that do not have category-to-category conflicts. The input matrix X in this stage is the relationship between the cat-
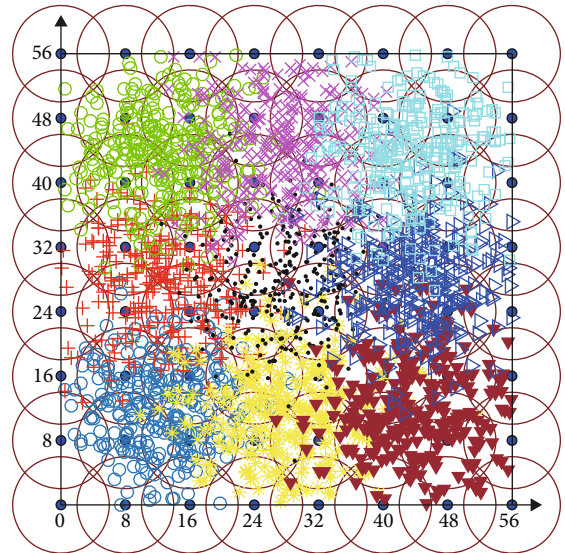

FIGURE 3: The composition of a large-scale RFID system.

egorized nodes, M is the number of colors, and the m is the number of categorized regions. The result is that category one and category three are in the same group, and category two is in another batch. These two groups will be scanned sequentially, and categories one and three will be scanned simultaneously.
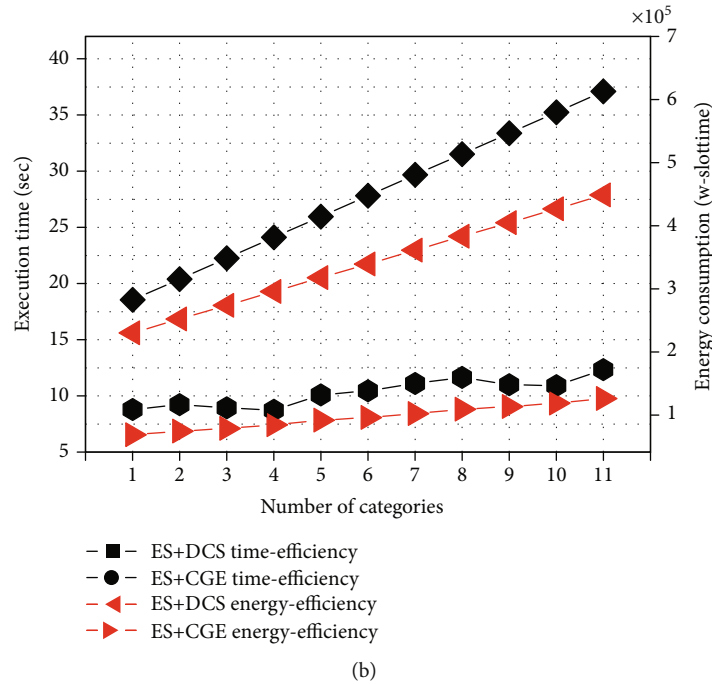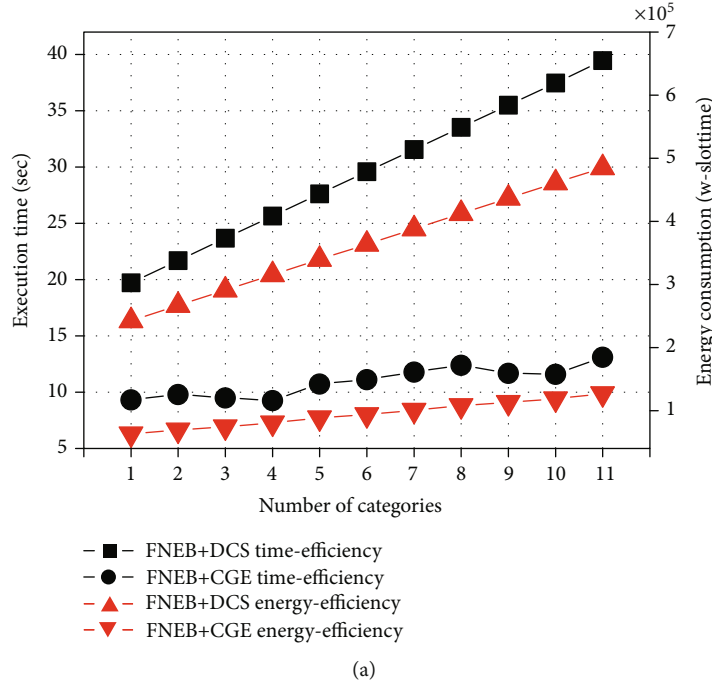
(a)

(b)

Figure 4: The comparisons between FNEB and ES based on our ECG and classic method DCS with the number of categories increasing.

(3) Coloring of the categorized readers: We assign names to the readers that monitor the tags in the same category; these are referred to as categorized readers. Although the work sequence of categories was determined in the previous phase, a single category of tags may be covered by multiple readers in the overlap regions. The overlap between readers causes reader-to-reader collisions (R2Rc), results in identification failure, and decreases the accuracy of tag estimation. To prevent R2Rc, we have to rearrange the order of operation of the readers. We use the Algorithm 1 to divide the readers into several groups in one categorized region. The input matrix X in this stage is the relationship between the categorized readers in one categorized region. Within each group, there are no overlaps between readers. Here, the M is the number of colors, and m is number of readers in each categorized
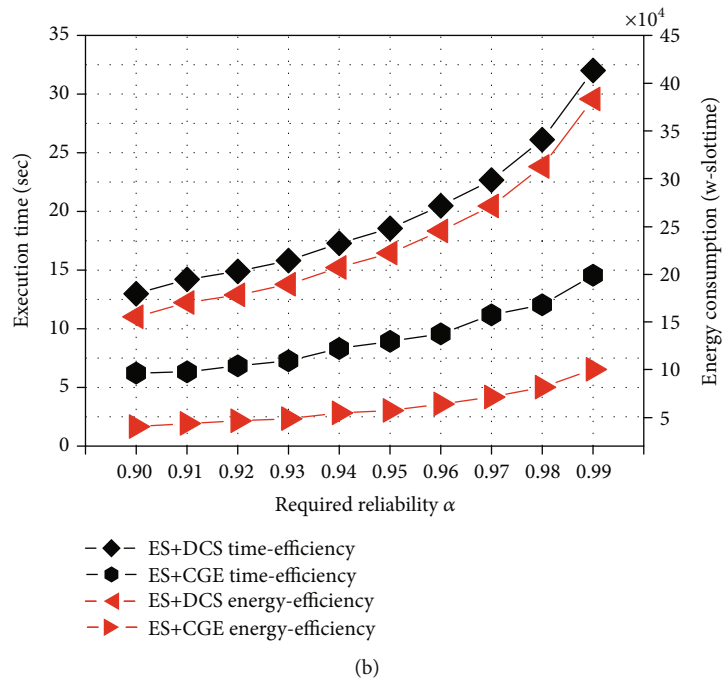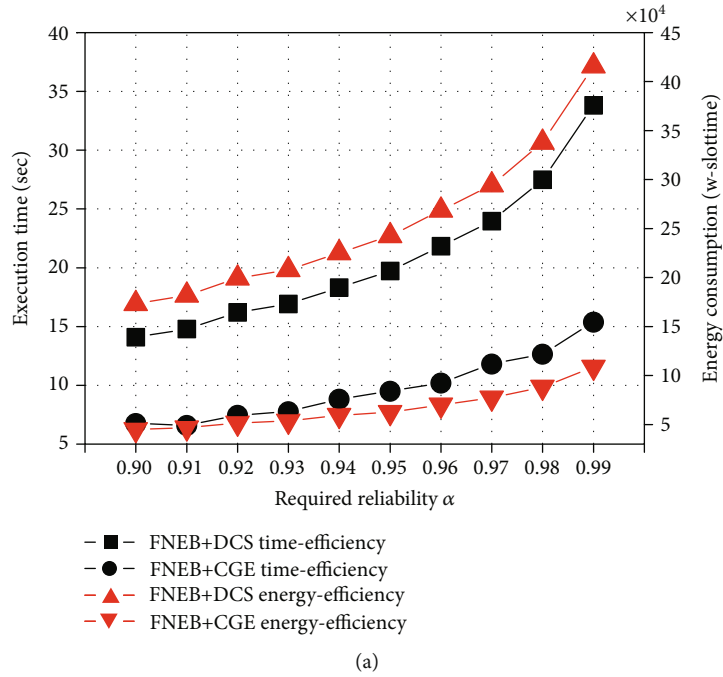
(a)

(b)

FIGURE 5: The comparisons between FNEB and ES based on our ECG and classic method DCS with α increasing.

distribution region. As illustrated in Figure 2(a), the readers in category two region are split into three groups: B_1, B_2, and B_3. The categorized readers R_1 and R_5 in B_1 will work simultaneously, R_3 and R_4 in B_2 and R_2 in B_3, and the working scheme of the categorized readers in B_2 and B_3 is the same as in B_1. B_1, B_2, and B_3 will work in sequence to avoid the R2Rc. The readers in categories one and three adopt the same method to split the readers. After that, every reader in the RFID

system is assigned the work sequence. For example, the six readers in Figure 2(a), one scheme is R_1, and R_3 work simultaneously in first, R_6 will work after R_1 and R_3 finish, and R_6 is done representing the estimation results of categories one and three that are obtained. The work sequence of readers in category two that has been introduced above

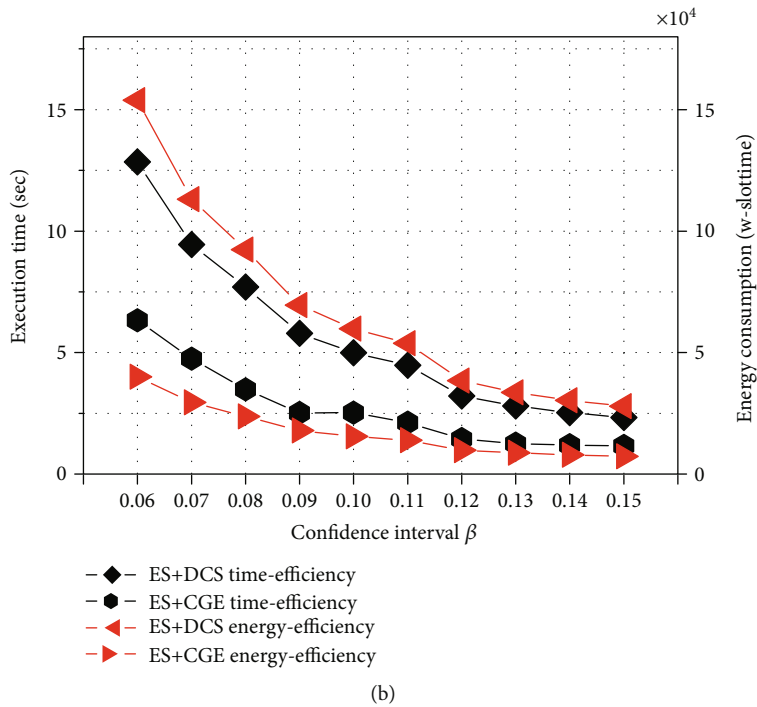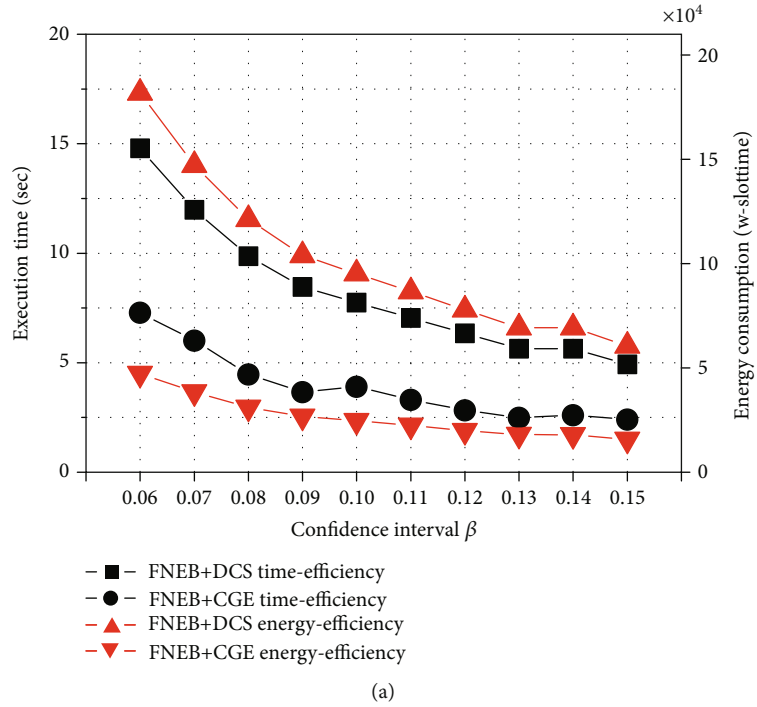(4) Estimation of the population size: After the former three stages, all the readers have been arranged to

(a)

(b)

FIGURE 6: The comparisons between FNEB and ES based on our ECG and classic method DCS with β increasing.

run in sequence for avoiding R2Rc. Since the tags in the overlapping zone covered by multiple readers will be counted more than once, the tag cardinality will be overestimated. To overcome this issue, we let all readers in one categorized region broadcast the same parameters. Since the tags use the hash function to select time slot to respond, tag's responses will appear in the slots of related frames with same index. Each

reader generates a binary frame vector, in which bit 1 indicates a busy slot and bit 0 indicates an empty slot. Then, we use OR operation to aggregate the frame vectors received from readers. Owning to the characteristics of the OR operation, multiple responses of a tag will only create one bit 1 in the aggregated frame vector. Thus, using the aggregated frame vector, the tag cardinality will not be
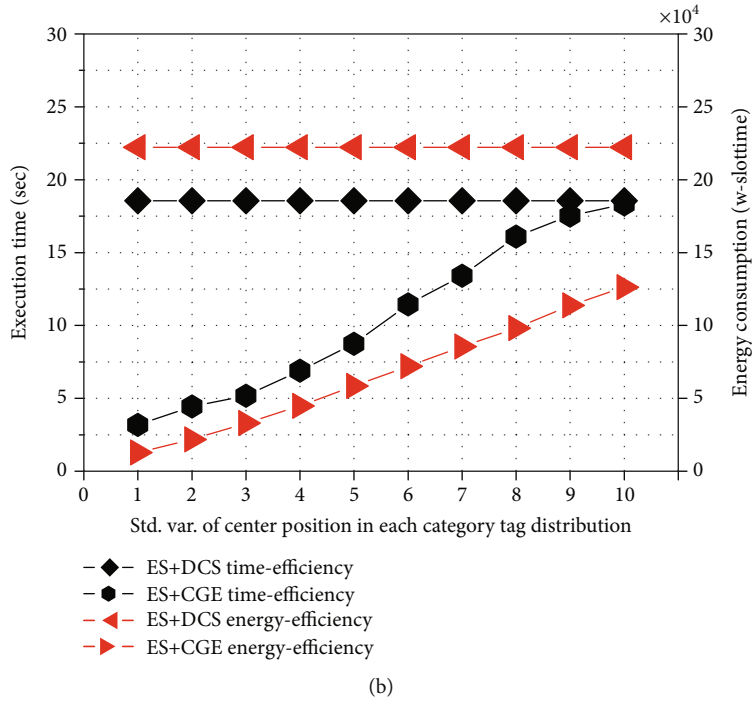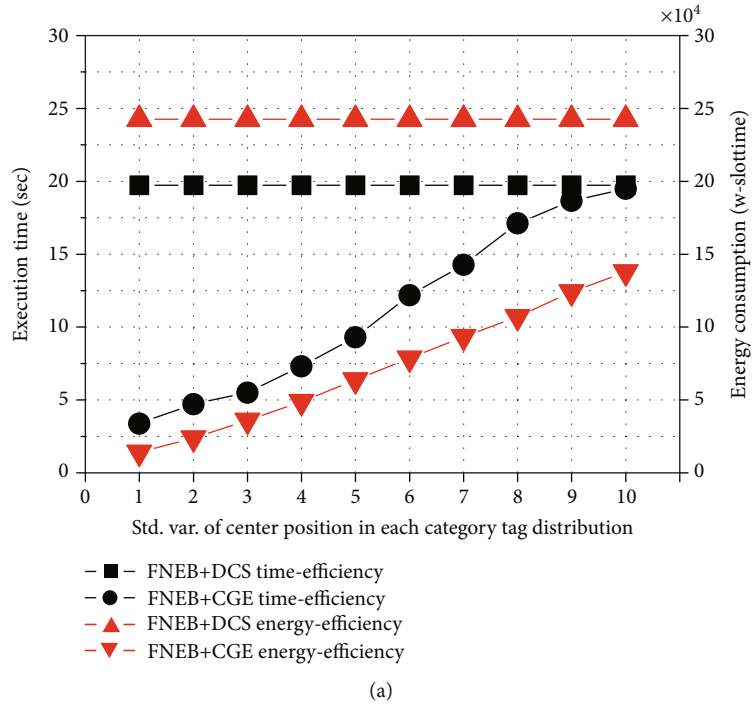
(a)

(b)

FIGURE 7: The comparisons between FNEB and ES based on our ECG and classic method DCS with σ increasing.

overestimated. In this stage, the previous estimation protocols FNEB [3], ES [1], etc. can be used in the ECG framework to estimate the population size of the tags. Unlike the exact tag identification schemes that need to resolve the tag-to-tag collisions, some probabilistic tag estimation schemes can benefit from the tag collisions, e.g., ART [23] and ZOE [24]. Hence, we do not optimize the frame size to reduce the tag-to-tag collisions. To ensure the convergence

of the results, we run the experiments independently for multiple rounds (i.e., 1000) and then calculate the average value [26–30]

3. Performance Evaluation

In this section, we demonstrate the performance of the proposed CGE. In the simulation, we implement the estimation protocols FNEB and ES based on our CGE scheduling

scheme and the classic reader scheduling method DCS and VDCS under the same parameters [11]. The precondition of the comparisons is that the locations of readers are known to us. For a fair comparison, each protocol uses the same wireless communication setting as follows. In term of time efficiency, the tag-to-reader transmission rate is 53Kb/s; otherwise, it is 26.5Kb/s. That is, it takes $18.8\,\mu s$ to transmit one bit from a tag to the reader, and $37.7\,\mu s$ to transmit one bit from a reader to a tag. Between two consecutive slots, there is a waiting time $\tau w = 302\,\mu s$ [8]. In terms of energy efficiency, the power of one query from reader is 825 mW, and the power of one bit response from reader is 125 mW [25]. In the experiment, we set the required reliability α that is 0.95, the confidence interval β is 0.05, the number of categories λ is 9, the number of tags in each category n_i is 1000, and the standard variance of the center position in each categorized tag distribution σ is 3. The communication radius of the reader is 6 m. In order to promote the understanding of readers, we show an example to illustrate the deployment of readers and the distribution of categories in Figure 3. The width and length of the monitoring area are 56 m and 56 m, respectively, and the communication radius of the reader is 6 m.

3.1. The Time Efficiency of Estimation. From Figures 4–7, we discover several observations as follows. First, the performance of the proposed CGE framework is better than that of the DCS and VDCS in terms of time efficiency. For example, when the data of required reliability α is 0.99, the time cost of the FNEB+DCS and ES + DCS is 33.44 s and 28.81 s, respectively. And the time cost of the FENB+VDCS and ES + VDCS is 37.23 s and 26.24 s, respectively. However, the time cost of the FNEB+CGE and ES + CGE is 13.53 and 12.80, respectively. It means that the CGE framework makes the FNEB and ES acquire 2.25× faster than DCS and 2.05× faster than VDCS at least. Second, the estimation time of the FNEB and ES increases as λ, α, increases, because the higher λ and α mean the stricter demand for achieving the required performance. In contrast, the estimation times of the FNEB and ES decrease as β increases. Third, the change speed of the FNEB+CGE and ES + CGE is lower than that of the FNEB+DCS and ES + DCS. Finally, the performance of the CGE depends on the distribution of the tag categories. The commodities, which tags are attached to, are more concentrated, and the time efficiency is higher which we discovered in Figure 7.

3.2. The Energy Efficiency of Estimation. In terms of energy efficiency, we discover three observations from Figures 4–7 as follows. First, the power consumption of the proposed CGE is lower than that of the classic scheduling method DCS. The power consumption of the ECG framework in the FNEB and ES methods is 72% lower than that of the DCS method, when the required reliability α of the RFID system is 0.99. Second, the energy cost of the FNEB and ES increases as λ and α increase and decrease as β increases. Finally, the power consumption of the DCS is not affected by the category distribution; however, the CGE takes advantage of the distribution of the categories, and multiple catego-

ries can be estimated simultaneously in one group. The simulation results show that the proposed CGE framework for estimating the tag population size results in higher time efficiency and less power consumption than the DCS method.

4. Conclusion

This paper proposed the CGE protocol for tag estimation in multireader and multicategory RFID systems. CGE discovers the interferences among categories and eliminates the reader-to-read collision by coloring the parallelizable categorized regions with the same color in two stages. CGE promotes the time efficiency of existing estimation algorithm because more regions can be parallelized for tag estimation in the multireader RFID system. And the simulation results illustrate the superiority of CGE under various parameters setting compared with other scheduling protocol.

Data Availability

The experimental data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The author(s) declare(s) that they have no conflicts of interest.

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