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Research Article

An Efficient Identification Algorithm to Identify Mobile RFID Tags

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Tag identification in a fast-moving environment is an emerging challenge for future RFID systems. However, existing literatures on the tag reading protocol design primarily apply to stationary scenarios, which fail to cope with mobile environments with unreliable channel condition. In this paper, we first review various types of prior reading protocols and then discuss a new direction of mobile tag reading by proposing a novel partitioning strategy. This analysis and experimental results show its superiority in achieving reading performance for the UHF RFID system under a mobile environment.

1. Introduction

With the advent of 5G mobile internet, the internet of everything will become a reality and be pervasively applied in our daily life [1]. It is reported that the number of global Internet of Things (IoT) [2, 3] connections will reach to 50 billion in 2020. As a key supporting technology for IoT, RFID has been boom developing in recent years. According to the analysis data in the IDTechEx market report [4], the total value of the global RFID market will be as high as 13.4 billion dollar in 2022, including readers, tags, and middleware for both passive and active RFID. IDTechEx also predicts that the sales of UHF RFID tags will increase from 15 billion dollar in 2019 to 41.2 billion dollars in 2024. The main applications are concentrated in areas including clothing label, air luggage, and inventory control. Since passive RFID can transmit wireless data with very little energy, this is especially important for some applications of IoT.

In recent years, the widespread use of passive RFID tags has promoted the development of various industries. For example, RFID tags can be widely used in the field of traffic transmission and easy access to existing departure control systems (DCS) and baggage reconciliation system (BRS). The introduction of RFID technology can enable airports to transport passenger's luggage more efficiently, quickly, and safely. Whether in the aviation industry or in other fields such as logistics warehousing and sales management [5], it is often necessary to accurately identify and sort the managed items through RFID technology in a mobile conveyor application scenario. The fundamental problem of these applications is how to accurately and effectively identify tags in a mobile scenario. Although the existing anticollision algorithms can solve the tag identification problem in a stationary scenario, there are still many new challenges in the identification of mobile tags. For example, the speed at which the object passes on the conveyor belt and the distance between the objects will affect the reading performance of the RFID system.

The conventional anticollision approaches consist of three categories: tree-based [6], Aloha-based, and their hybrid [7, 8]. Most of previous works focus on how to optimize the parameters when identifying static RFID tags under a stationary scenario [9]. However, in actual RFID applications, the status of the reader and tags will change over time, such as path loss, signal attenuation, and tags moving away from the reader's coverage, can lower the reading performance. Hence, the conventional anticollision solutions are difficult to adapt to a mobile environment. Focusing on tag moving scenario, some literatures [10, 11] have presented corresponding approaches to optimize the identification performance of RFID network. In the tag moving scenario, these previous strategies [10, 11] consider some previously identified tags (they are called staying tags) stay in the reader vicinity in the ongoing frames, and some new arrival tags participate in the current reading process. Moreover, they use bit tracking technology (a technology that can accurately identify and locate the collided bit) to improve the reading performance. However, in the reverse link of UHF RFID system, the deviation in the backscatter link frequency (BLF) of various tags can be as high as plus or minus 22% [4], which causes the received data at the reader side is asynchronous. Therefore, these methods have not been adopted by mainstream UHF national standards, and their scope of implementation is limited. Based on the same tag moving scenario, literature [12] proposes a tree-based algorithm to reduce the identification time. Also, some works [13, 14] revealed the characteristics of the physical layer like signal attenuation and shadowing effects through experimental means, which will have a serious impact on the identification performance of RFID systems.

In the following sections, we provide an overview of various prior anticollision mechanisms and analyze the limitations of them in a realistic RFID environment. Furthermore, to cope with the fundamental limitations of the prior anticollision solutions, we present a novel partitioning-based anticollision algorithm (PBAA) to identify tags under a mobile scenario with the unreliable channel. Our proposed PBAA optimizes the mathematical expression of the probabilities of collision, empty, and success slots in the mobile RFID scenario, thereby effectively combining the tag number estimation and frame length setting.

The rest of this paper is structured as follows. Section 2 conducts a survey and taxonomy of the existing tag reading protocols. A new tag reading strategy suitable for a mobile environment is elaborated in Section 3. Section 4 evaluates our proposed algorithm and compares the experimental results. Finally, the conclusions are summarized in Section 5.

2. Review of Tag Reading Protocol in RFID

The RFID tag reading or anticollision problem is to identify a given set of tags within the reader's coverage as fast as possible. Most of the literatures and industrial applications define this problem as follows: Given a batch of tags, each tag is equipped with a unique identifier (ID) and is affixed on object to being identified. The user expects to quickly and efficiently recognize all tags with a handheld reader or a fixed reader. Since the channel between the reader and tags is shared, thus, the anticollision algorithm or tag reading protocol is required. In what follows, we will firstly review the existing tag reading protocols. Then, we will conduct a taxonomy of the existing solutions from multiple perspectives. Table 1 summarizes the features of various tag reading solutions.

2.1. Probabilistic Algorithms. Among Aloha-based algorithms, the dynamic framed slotted Aloha (DFSA) algorithm is the most typical representative. In DFSA algorithm, any tag attempts to reply a query submitted by the reader with its ID information at a randomly selected time slot of a frame. The working principle of DFSA is illustrated in Figure 1.

The performance of DFSA is mainly affected by two factors: one is the accuracy of cardinality estimation and the other is the setting of frame length. As the accuracy of the cardinality estimation increases, the complexity of the algorithm will become increasingly higher. In fact, it is proved that the DFSA algorithms with high mathematical and computational costs are energy inefficient [15]. The tag identification strategy based on subframe observation (TES-FAS) [15] is proposed to reduce the overall error. However, since its empirical correction in estimation is only based on a stationary RFID system, the accuracy may be not sufficient for a mobile RFID system. The literature [16] proposed a schedule-based tag identification (SAC) approach, which determines the maximum moving speed of a tag that satisfies a given identification rate. The mechanism of SAC is to divide the tag set into smaller subsets and assign the different identification priorities for various subsets.

2.2. Deterministic Algorithms. Unlike probabilistic solutions, the deterministic algorithm uses tag ID to separate the colliding tag set instead of the random number. Among deterministic algorithms, a query tree- (QT-) based algorithm is a typical representative. In QT-based algorithm, the reader queries tags with a binary string (called query prefix), and the tags whose IDs match the query prefix will respond. Once detecting a collided string from the tags, the reader will probe again after appending the previous query prefix by 0 and 1, respectively. This query-and-append loop continues until all tags are successfully identified. An identification example of a QT-based algorithm is show in Figure 2. In the example, there are four tags with IDs of (001, 011, 100, 110) waiting to be identified in the reader's coverage. The reader firstly probes the tags with the prefix 0 and then probes tags with the prefix 1. As can be found in Figure 2, the reader consumes 8 slots in total to identify the above four tags. In the tag identification process, there are four empty queries and six collision queries. Many past works focus on how to effectively reduce the number of collisions and identification time in stationary scenarios. However, they may fail in various mobile scenarios. For example, some new arriving tags participate in the current reading process, if their IDs are less than that of tags that have been identified, they will be a missing read.

Based on QT-based strategies, some algorithms [10, 11] have been presented to optimize the reading performance for a tag moving scenario. The literature [10] presented a dynamic anticollision solution named dynamic collision tree (DCT) protocol which updates query string and splits the colliding tag set based on the first collided bit. In DCT, when a new arriving tag participates in the current reading process, two new nodes are inserted in the traversal tree according to the tag's ID. However, it is very difficult to know the IDs of tags in advance. In [11], the authors present a scheme based on bit monitoring to determine the presence of identified tags which stay in the reader's coverage, and an M-ary collision bit-based query mechanism is introduced to

Table 1: The characteristics of various tag reading protocols.

Type	Algorithm	Slot efficiency	Time efficiency	Cardinality insensitive	Tag moving	Resist capture effect	Resist path loss	Implement to EPC C1 GeN2
DFSA	TES-FAS [15]	High	High	✗	✗	✗	✗	Very easy
	SAC [16]	High	High	✗	✓	✗	✗	Medium
	DP [17]	High	Medium	✗	✓	✗	✓	Medium
	PBAA	Very high	Very high	✗	✓	✓	✓	Easy
QT	TH [9]	Very high	Medium	✓	✗	✗	✗	Difficult
	DCT [10]	Very high	Medium	✓	✓	✗	✗	Difficult
	EBD [11]	Very high	High	✓	✓	✗	✗	Difficult
TS	RBA [12]	High	Low	✓	✓	✗	✗	Medium
	SSRB [18]	High	Medium	✓	✓	✗	✗	Medium
Hybrid	ABTSA [19]	Very high	Medium	✗	✗	✗	✗	Difficult

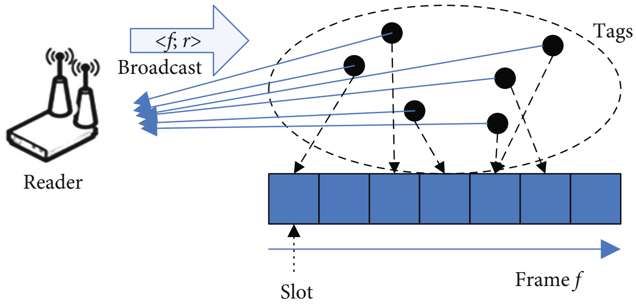


Figure 1: The working principle of DFSA algorithm.

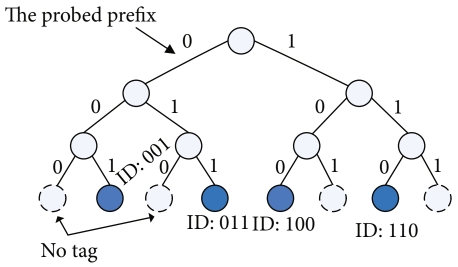


Figure 2: An illustrative example to identify four tags in the QT-based algorithm.

rapidly recognize the new arriving tags. Although the above solutions can improve the reading performance under the scenario that the tags are put on the moving conveyor belt, they are essentially dependent on bit tracking technology which is difficult to implement in the UHF RFID systems [8].

2.3. Hybrid Algorithm. There are many studies that attempt to integrate the characteristics of different algorithms to further improve the identification performance and thus develop various hybrid algorithms. The authors in [19] propose a hybrid algorithm named the tree slotted Aloha with adaptive binary splitting (ABTSA) which incorporates features of the Aloha-based and TS-based algorithms. ABTSA determines whether the current frame length is appropriate by monitoring the status of each slot. If it is appropriate, the TS-based algorithm is activated to resolve the collided slot; otherwise, the current frame length is readjusted. Although ABTSA can achieve a higher slot efficiency, it is time consuming due to identifying the collided tags in the TS manner.

In summary, the aforementioned anticollision algorithms can alleviate the tag collision to a certain extent; however, it suffers from serious challenges due to the complex realistic environment. All of the above solutions suppose that the communication link between the reader and tags is error free, without fully exploring many challenges in the actual situation, such as shadowing effect and blind spot. However, the instability of the practical communication links can seriously handicap the identification performance of RFID systems. Many works attempt to explore the impact of physical layer characteristics on reading performance through an experimental observation method. The authors in [13] verify the performance of RFID systems based on EPC C1 Gen2 standard using the testbed. Their research observations show that the physical and MAC layers should be considered in conjunction rather than separately as is done. The literature [14] presents the reliability of a method for estimating in a real measurement environment. However, in the work, only the capture effect is considered, and the path loss and other radio propagation issues are not fully explored. The authors in the literature [17] tested that mobile RFID tag reading is significantly affected by the influence conditions such as speed of moving tags and angle of antenna and further verified that physical and MAC layers should be considered at integrally. In the following, an efficient tag reading protocol is proposed to overcome the above challenges. The proposed solution is aimed at achieving both slot efficiency and time efficiency in a mobile environment.

3. A New Design of Efficient Reading Strategy under an Unreliable Channel

3.1. System Model. There are two communication links in the UHF RFID system, namely, downlink and uplink, respectively. Among these two links, the uplink represents the communication link from the tag end to the reader end, while the downlink represents the communication link from the reader end to the tag end. The international standard EPC C1 Gen2 of UHF RFID has strict specification on the timing of the communication links, which is shown in Figure 3. In the downlink, the reader continues to send a carrier wave to the tags, and for one thing, each tag absorbs energy from the RF wave to meet its own energy consumption. For another, each tag parses the command data included in the carrier wave sent by the reader in order to respond. In the uplink, the tag replies to the reader based on the parsed command data, and the response data is modulated onto the reflected carrier using FM0 or Miller coding. This modulation method is called backscatter modulation. The tag implements data transmission on the reverse link by backscatter modulation. In order to successfully read a tag in a UHF RFID system, two prerequisites need to be met. First, the receiving power $P_{(\mathrm{tag},rx)}$ of the tag needs to be higher than the sensitivity P_{st} of the tag itself. Only in this way can the tag absorb enough energy to meet its own needs. Secondly, the receiving power $P_{(\mathrm{reader},rx)}$ of the reader is higher than the sensitivity P_{rt} of the reader itself. Only in this way can the reader correctly decode the signals returned by the tags. The sensitivities of the tag or reader represent the minimal energy required to maintain their own work. As can be seen in Figure 1, there are three possible outcomes for a given time slot: no reply (empty slot), single reply (singleton slot), and multiple replies (collision slot). However, in the actual identification process, the communication link between the reader and tags is not always steady. For example, Figure 4(a) illustrates the scenario of identifying moving tags. In such a case, the reader's identification of tags will become extremely complicated, because of the existence of factors such as object moving, multipath, and capture effect. These factors make the originally assumptions about channel ideals no longer realistic. Figure 4(b) shows the translation relationship from a time slot in a stationary environment to a time slot in a more practical environment. Herein, P_{trR} represents the probability that a tag can acquire the reader's command correctly, and P_{Rrt} means the probability that the reader is able to parse the response from the tags. The $P_{\mathrm{c}->\mathrm{s}}$ and $P_{\mathrm{c}->\mathrm{e}}$ denotes the probability that original multiple replies in a steady channel model transfer into a singleton slot and an empty slot, respectively, which can be expressed as the function of P_{Rrt}. α denotes the occurrence probability of the capture effect. Under such conditions, the conventional tag reading solutions used in the stationary model will no longer be applicable. Therefore, it is critical to develop reading strategies based on a mobile model to tackle the tag collision problem.

3.2. Cardinality Estimation under the Unreliable Channel. In an actual RFID application paradigm, physical layer features such as multipath and capture effect, path loss, and attenuation all occur probabilistically. In order to characterize these features, we built a dynamic tag identification model and design the corresponding tag number estimation method based on this model. Assuming that there are n tags in the radiation range of an RFID reader, the reader uses an initial frame of length F to identify them. Accordingly, in our proposed probabilistic model, tags do not respond to the reader 100%, so in a frame, the number of tags that respond is $\hat{n} = n \cdot (P_{trR})^2$. Similarly, the probability P_m that m tags simultaneously select a time slot under our model can be calculated using binomial distribution. Combining the translation relationship described in Figure 4 and the existing analytical method, the reader can estimate the parameters of n, P_{trR}, P_{Rrt} and α. We can establish a scenario with only a single reader and single tag and then use an experimental testing method to obtain the values of these parameters. The specific method is as follows: we can place the tag at different distances d from the reader antenna. We first set the frame length F to 1, then let the reader attempt to read the tag k times repeatedly, and record the number of times m_1 that the tag is successfully identified. Then, we find a ratio as $r_1 = k_1/k$. Secondly, we increase the F value from 1 to a large number such as 256 and also let the reader independently recognize the same tag k rounds and obtain the number of times reading k_2 that the tag is successfully identified. Similarly, we can obtain a ratio as $r_2 = k_2/k$. In what follows, we can setup a scenario with only a single reader and multiple tags and set the frame length F to 1. We allow the reader to independently recognize a tag k rounds and obtain the number k_3 of times that the tag is successfully identified. Accordingly, we can obtain a ratio as $r_3 = k_3/k$. Hence, the environment parameters P_{trR}, P_{Rrt}, and α are expressed as

$$\alpha = \frac{r_3}{r_1} = \frac{k_3}{k_1}, \tag{1}$$

$$P_{trR} = \frac{r_2}{r_1} = \frac{k_2}{k_1}, \tag{2}$$

$$P_{Rrt} = \frac{k_1}{k_{21}} \sqrt{\frac{k_1}{k}}. \tag{3}$$

We can precalculate and save the values of these parameters for different distances. As a result, we can reduce the computational complexity in the tag number estimation phase.

3.3. The Partitioning-Based Identification Phase. According to the mentioned estimation method, the reader can get an approximate value of the number of tags n, P_{trR}, P_{Rrt}, and α. Instead of assigning a single full frame for the unread tags in conventional DFSA algorithms, the proposed PBAA solution divides unread tags into N subsets averagely according to the estimated n, P_{trR}, P_{Rrt}, and α. Then, the reader conducts the corresponding identification process on individual subsets. Each process is named a partitioning-based identification phase. The workflow of the partitioning-based

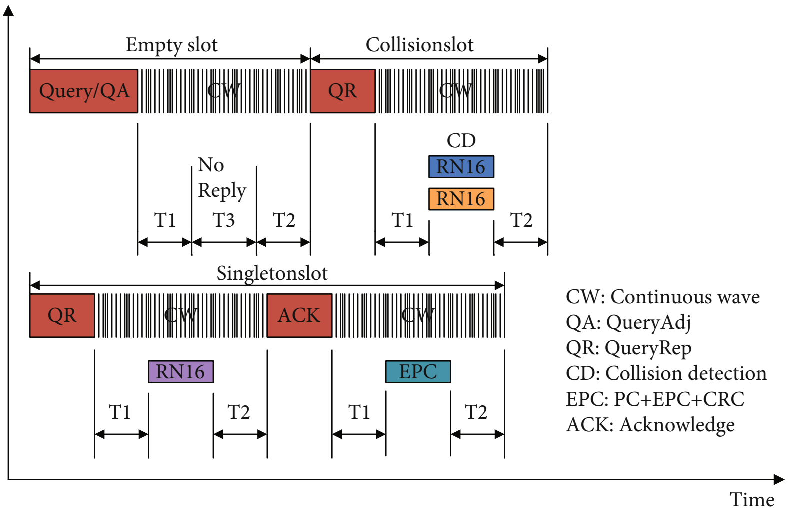
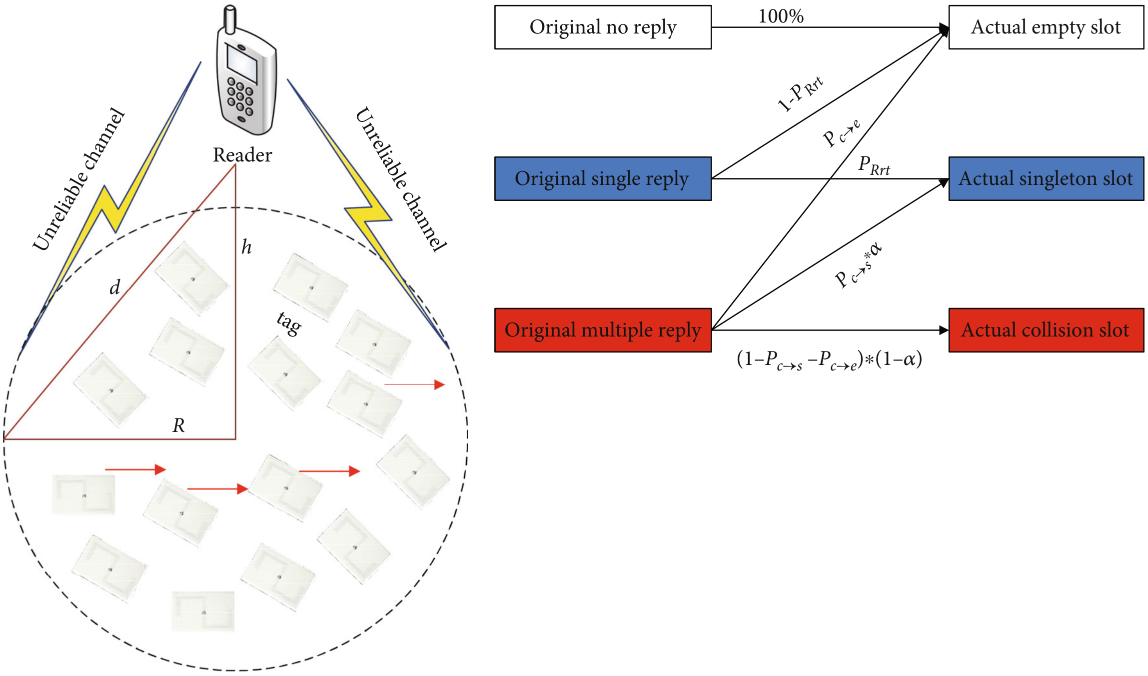


Figure 3: The link timing specified by EPC C1 Gen2.



(a) (b)

Figure 4: The tag reading under a mobile scenario.

identification phase is described as follows. The reader will fix the frame length to 2 to initiate an identification process for each subset, which is called the IIP process. The detailed working process of IIP is shown in Figure 5, where F means the initial frame size, N_{id} means the number of identified tags, and C means the number of collision slots. The reader triggers the reading process slot by slot and records its feedback results. If no response is monitored, the reader will increase the number of empty slots by one. If multiple responses are monitored, the reader will trigger the second slot and increase the number of collision slot by one. When a single response is monitored, the reader will directly read the tag and increases the number of singleton slot by one. The reader will iteratively execute the above identification process until all tags are completely identified. Since the above process does not need to estimate the number of unread tags, the problem of misreading will be alleviated due to the unreliable channel. Thus, with the introduction of IIP in the reading protocol, the identification efficiency of RFID in a mobile scenario will be significantly improved.

4. Evaluation Discussion

4.1. Simulation Setup. In this section, we evaluate the performance of PBAA and compare it with prior arts including TES-FAS [15], RBA [12], DP [17], and SAC [16] over

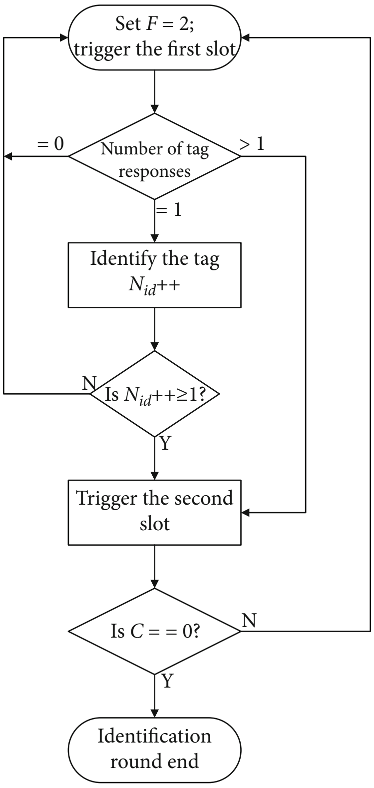


Figure 5: The detailed working principle of the IIP process.

Table 2: The link parameter setting between the reader and tag communication.

Experimental scenario	A	B
R- > T modulation	PR-ASK	DSB-ASK
R- > T coding	PIE	PIE
Tari (us)	25	6.25
PW (us)	12.5	3.13
RTcal (us)	62.5	15.63
TRcal (us)	85.33	20
DR	21.33	8
T- > R modulation	Miller-4	FM0
TRExt	1	1
BLF (kHz)	250	400
Data rate (kbps)	62.5	400
Tag moving speed	1 m/s	2 m/s

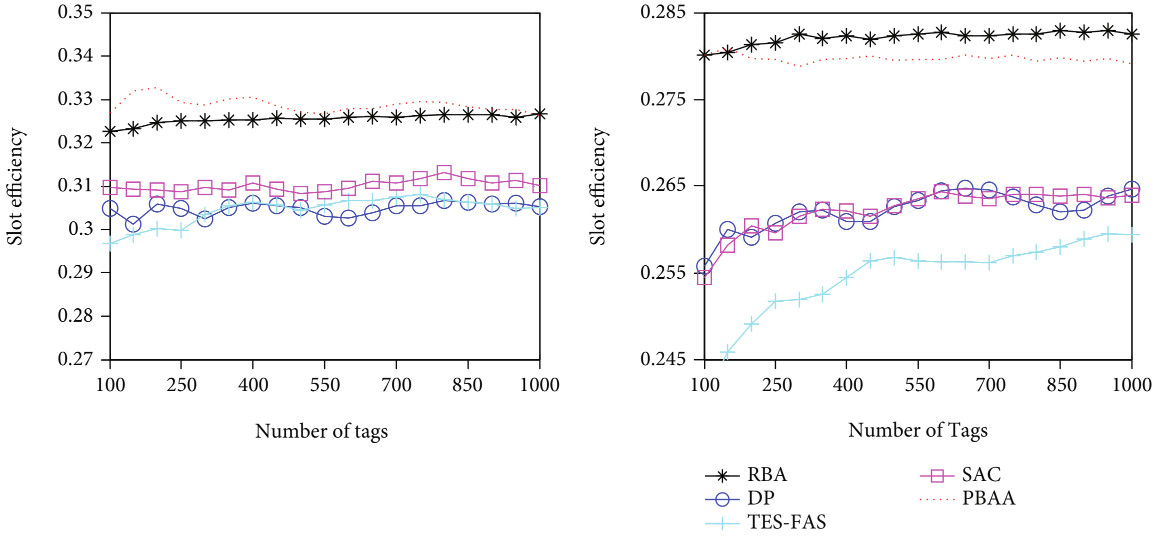
extensive Monte Carlo simulations. The reader's coverage is a circle with a radius of 6 meters. In our simulations, we consider a scenario of reading moving tags on the conveyor, where the distance between the reader and the horizontal line is 2 meters. To ensure the robustness of the results, in the simulation, 1000 iterations are run to obtain each result [8, 15, 16, 20]. The parameters used in MATLAB simulation are listed in Table 2.

In order to better measure the performance of our proposed algorithm, we use the following two metrics: (1) slot efficiency, defined as the number of singleton slots over the total number of slots to identify all tags and (2) time efficiency, which is widely used in literatures and it can better reflect the performance of an algorithm in the time dimension.

We compared our proposed algorithm PBAA with other advanced algorithms in detail between the two performance evaluation metrics described above. In order to provide a more comprehensive and fair comparison, we choose some representatives in both TS-based and Aloha-based algorithms. Specifically, RBA [10] is the representative of TS-based algorithm. The representatives of Aloha-based algorithms are TES-FAS [15], SAC [16], and DP [17].

4.2. Results on Numerous Metrics. Figure 6(a) depicts the slot efficiency of comparative approaches under scenario A. The size of tag cardinality is between 100 and 1000 in steps of 50. The frame length is initialized as 64. Observed from the results, the proposed PBAA can always maintain a more stable and higher performance. The reason why the proposed anticollision algorithm PBAA can achieve such improvement is twofold. For one thing, the proposed estimation strategy can obtain the accurate estimation results of the number of tags to be identified n_{est}, the probability that the tag can correctly receive the reader's command P_{trR}, and the occurrence probability of capture effect α. For the others, the proposed IIP process can alleviate the negative impacts on reading performance caused by path loss and capture effects. The slot efficiency of RBA is higher than that of other Aloha-based algorithms because it allows all of unread tags to respond to the reader at the following slots. It somewhat reduces the impact of channel uncertainly on slot efficiency. On the contrary, Aloha-based algorithms are more susceptible to factors such as path loss and capture effect. Thus, their slot efficiency is lower than that of tree-based algorithm. Figure 6(b) plots the slot efficiency under scenario B. As can be observed, some algorithms show discrepant performance. For example, the average slot efficiency of TES-FAS is close to DP and SAC when tag moving speed is 1 meter per second. However, its slot efficiency is lowest when the moving speed is increased to 2 meters per second. The reason is that the mechanism of TES-FAS including cardinality estimation and frame length setting is optimized based on ideal channel conditions. As the channel conditions deteriorate, the TES-FAS is increasingly unable to adjust an appropriate frame length to fit the unread tags, resulting in sharply performance degradation. Since the frame length setting and cardinality estimation are based on variable channel conditions, the PBAA can always maintain the better slot efficiency compared to reference solutions.

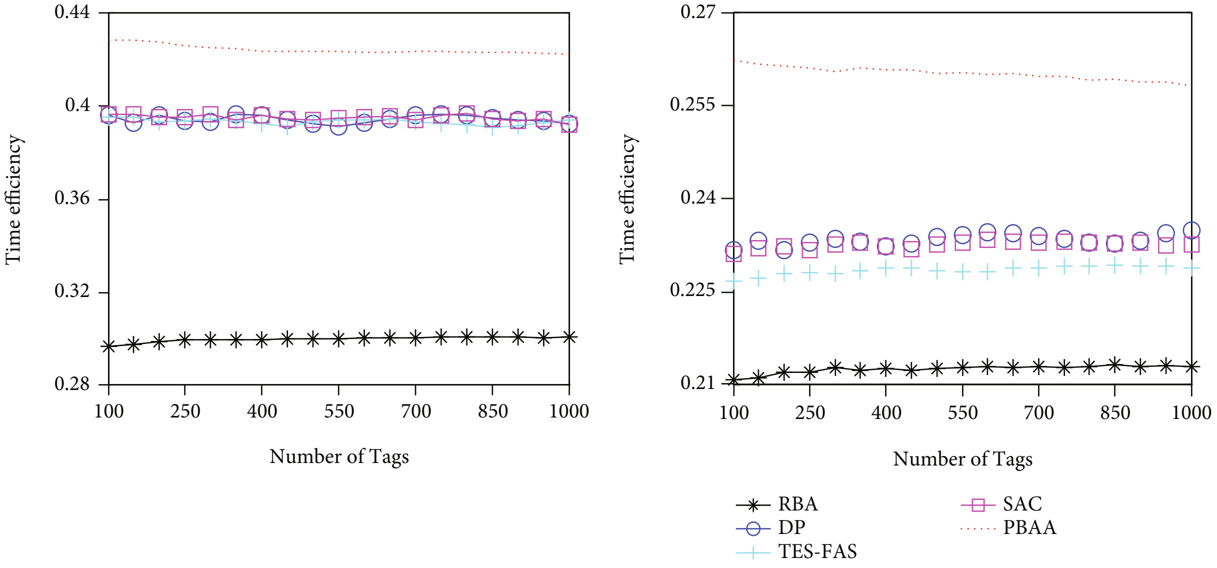
To compare the identification performance of various solutions from a time perspective, Figure 7 illustrates the time efficiency of all methods under different scenarios. Where scenario A is in low-rate mode (date rate ≤ 80 kbps), scenario B is in high-rate mode (date rate ≥320 kbps). It can be seen from Figure 4(a) that the performance ranking of algorithms from the highest to the lowest is PBAA, SAC, DP, TES-FAS, and RBA. Such ranking is different with the ranking observed in Figure 6(a). For example, RBA is



(a)

(b)

Figure 6: Simulation results: comparison of various methods in slot efficiency.



(a)

(b)

Figure 7: Simulation results: comparison of various methods in time efficiency.

superior to SAC, DP, and TES-FAS in terms of slot efficiency. However, its time efficiency is lowest. The reason is analyzed in Section 2. The time efficiency metric takes into account both the slot type and the slot duration. Thus, our proposed PBAA performs exceptionally well in this evaluation metric. The reasons are summarized as follows. When the reader uses the PBAA algorithm to identify the tags, the number of empty slots consumed is much greater than collision slots, and the occupied time duration of each empty slot is much shorter than collision slot. Explicitly, the time efficiency should increase as the data rate increases. However, the opposite is true. Observed from Figure 7(b), the performance of all algorithms deteriorates under scenario B where the moving speed is 2 meters per second. The reason is as follows. As the moving speed increases, the tag quantity that can be read in a frame drops significantly due to the deteriorative channel, causing many time slots to be wasted and thus prolonging the total identification time. Therefore, the time efficiency will be degraded. For example, the TES-FAS provides the constrained formula between the probabilities that a slot is collided or empty based on the consumption that the communication link is ideal. However, such constraints are not suitable for the nonideal case. As the P_{trR} decreases, the performance deterioration will get worse. We can see from the Figure 7(b) that the time efficiency of TES-FAS is lowest. Unlike conventional DSFA algorithms, our proposed PBAA can estimate the P_{trR} and α, thereby eliminating their negative impact on mobile RFID tag identification performance. Both benefiting from the designed estimation strategy and partitioning-based identification phase, our proposed PBAA can achieve the highest performance in terms of slot efficiency and time efficiency under mobile RFID tag identification scenarios.

5. Conclusion

In this paper, we make the following key contributions. First, we analyze and discuss the drawbacks of various tag reading protocols especially on the performance of the MAC layer under mobile scenarios with the unreliable channel. Different from conventional DFSA approaches in a stationary scenario, the PBAA can adaptively obtain an accurate estimation value of the environment parameters and hence optimize the reading performance. In our view, our proposed PBAA solution makes RFID capable of adapting to mobile scenarios with the unreliable channel and meeting the IoT application requirements of time efficiency and high slot efficiency. The new results on the reading performance obtained in this paper can provide a valuable reference and guideline for the practical RFID system under the mobile environment.

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 authors declare that they have no conflicts of interest.

Acknowledgments

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