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Abstract In this paper, we study radio frequency identification tag identification problems using framed slotted ALOHA protocol. Each tag will be assumed to participate in the contention with a certain probability. Then, the frame size and the probability will be dynamically controlled by the reader in every reading round so that all the tags can be detected in a short period of time. Moreover, we propose a practical way of controlling the probability in terms of transmit power control, assuming Additive White Gaussian Noise channel or flat Rayleigh fading channel. Computer simulation results demonstrate the effectiveness of the proposed method.

Keywords RFID · Tag identification · Framed slotted ALOHA · Transmit power control

1 Introduction

Radio frequency identification (RFID) technology has become very popular in many applications of identifying objects automatically. Some of them are inventory control and tracking,

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medical patient management and security check [1–3]. In RFID systems, the reader tries to identify all tags by firstly transmitting an inquiring command to initiate the communication, and then, upon hearing the reader's command, tags respond with their identity (ID). However, as multiple tags may respond to the reader simultaneously, the tags' replied packets will collide and be lost. To overcome this challenge, some anti-collision identification algorithms, which can be classified into two main approaches: tree-based [4] (binary tree) and ALOHA-based [5] (framed slotted ALOHA), are proposed.

The binary tree algorithm is adopted by the international standard ISO 18000-6B [6], which is based on tree searching [7]. In the algorithm, colliding tags in a time slot continuously try to re-respond to the reader by selecting one of the two successive time slots until they succeed. Also, in order to cope with limitations of RFID systems such as constraints on memory and computational capabilities, a few variants of the algorithm, which are Binary Search [1], Query-Tree [8], and Binary Tree Traversal [9], have been implemented. The binary tree algorithm is efficient when the number of tags is small, however, it experiences consecutive collisions, which is subject to a longer identification time comparing to ALOHA-based algorithms, for a large tag cardinality. Indeed, it is proved in [10] that the total identification time for the binary tree algorithm is more than that for the Framed Slotted ALOHA (FSA) algorithm to complete the identification process. Moreover, the binary tree algorithm requires much more reading rounds than FSA algorithm, which results in larger overhead. Due to the simplicity and robustness, ALOHA-based algorithms are widely used in RFID standards [11].

In FSA-based tag identification algorithms, the reader probes the tags using a frame composed of time slots, where each tag randomly picks a slot in the frame to transmit, which is referred as a contention process. To improve the efficiency of the algorithms, Dynamic Framed Slotted ALOHA (DFSA) protocol [12–17] is proposed in which the frame size is dynamically controlled by the reader in every reading round depending on the observed slots. Two common methods for controlling the frame size in DFSA are Q algorithm [14] and Log algorithm [15]. Specifically, in Q algorithm, the next frame size is determined based on the observed number of empty, collision slots in the current reading round, while in Log algorithm, the frame size is found using the estimated number of undetected tags. In fact, it is proved that optimal system efficiency, in which the number of detected tags is maximum in each reading round, can be obtained when the frame size is equal to the number of tags. However, the optimality is difficult to achieve in practice because the total number of tags is unknown a priori. Moreover, as the total number of tags is increased, the protocol becomes usually inefficient since the choice of the frame size is limited due to hardware constraints [18,19], although a very large tag cardinality could be estimated by extracting the information from collisions with Lottery Frame (LoF) protocol [20]. Indeed, in [18] and [21], the frame sizes are under the form 2^Q where the maximal values of Q are set to 256 and 512 respectively.

There are some methods dealing with this problem. For example, in [22], transmit power can be controlled to cluster the tags in distance ascending order from the reader, however, this method is only applied to tree-based algorithms. Note that the reader could utilize both the tree-based and ALOHA-based algorithms, in which tags are first split into multiple subgroups through the tree-based algorithm with binary suffix strings, and then the ALOHA-based algorithm is used to identify tags in each subgroup [23]. However, when the number of tags is very large, the splitting process, which is based on the estimate of the tag cardinality, could not be efficient because the estimate is usually inaccurate, while it also takes much time before the usage of the ALOHA-based algorithm. Another approach is deploying multiple readers with overlapping interrogation zones [24,25], but the disadvantages of these methods are high cost, system complexity, reader-to-reader interference [26] and the readers' optimal placement [27,28]. On the other hand, Kodialam and Nandagopal [29] propose a protocol using a probability, which is called probabilistic framed slotted ALOHA (PFSA), in order to deal with the tag set cardinality estimation problem when the total number of tags is very large. In this case, the reader may inform a fixed frame size L and a parameter $p \in (0, 1]$ and then, each tag is assumed to participate in the contention process with the probability p. However, the scope of Kodialam and Nandagopal [29] is mainly focused on the tag set cardinality estimation, while the tag identification problem is not investigated in the paper, although it is straightforward to apply PFSA to the identification problem.

In this paper, we study the tag identification problem in a situation that the number of tags might be much greater than the maximal frame size. For a given way of estimating the tag cardinality, the optimal system efficiency can be obtained in each reading round, regardless of the limitedly chosen frame sizes, by the proposed protocol: Probabilistic Dynamic Framed Slotted ALOHA (PDFSA), where the definition of the transmission probability p is utilized. In particular, the frame size and the transmission probability are controlled in each reading round in order to maximize the channel usage efficiency (CUE), which is defined as a ratio of average number of singleton slots to the frame size by which all the tags can be detected in a short period of time. Moreover, we propose a practical way of implementing PDFSA using transmission power control, assuming Additive White Gaussian Noise (AWGN) channel or flat Rayleigh fading channel. Computer simulations will be performed proving the effectiveness of the proposed method comparing to conventional methods.

The rest of this paper is organized as follows. In Sect. 2, the system model and the conventional approaches are described. Sections 3 and 4 provide the proposed method in detail and simulation results are shown in Sect. 5. Finally, we conclude in Sect. 6.

2 System Model and Conventional Approaches

2.1 System Model

The considered RFID system consists of a reader and n unknown tags. In the rth reading round, the reader first transmits a time slotted frame with size L_r. Then, each tag randomly selects one of the available time slots and transmits its ID at the selected time slot [16]. After reception of IDs at the reader, if a slot j has no transmission or only one transmission, then we refer to this slot as an empty or singleton slot, respectively. If multiple tags transmit in the same slot j, we refer to slot j as a collision slot. The reader observes E_r empty, S_r singleton and C_r collision slots where $L_r = E_r + S_r + C_r$. The reading process is repeated until all the tags are identified. Note that, the frame size is limited due to hardware constraints and in this paper, it is under the form of 2^Q [21], where $Q = 0, 1, 2, \ldots, 8$.

2.2 Conventional Approaches

2.2.1 DFSA

In DFSA protocol, the frame size is dynamically controlled in each reading round for efficient tag identification. In particular, in the rth reading round, the CUE [16] is defined by the expected value of the number of singleton slots $\bar{S}_r$ divided by the frame size L_r as

$$\mathrm{CUE} = \frac{\bar{S}_r}{L_r} = \frac{n_r}{L_r}\left(1 - \frac{1}{L_r}\right)^{n_r - 1}, \tag{1}$$

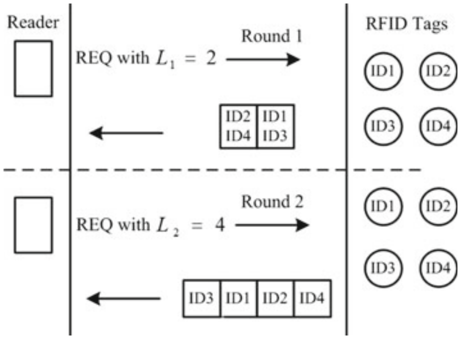


Fig. 1 Anticollision process with dynamic framed ALOHA

where n_r is the number of undetected tags before rth reading round. In order to obtain the optimal CUE, the derivative of (1) with respect to L_r is set to zero by continuous relaxation, which results in $L_r = n_r$. Then, Log algorithm [15] determines the frame size by

$$L_r = 2^{\text{round}(\log_2(n_{\text{est},r}))}, \tag{2}$$

where round(X) rounds the value of X to the nearest integer, and $n_{\text{est},r}$ is the estimate of n_r, which can be found by Schoute method [30] or Vogt [18] method. Specifically, using Vogt method, $n_{\text{est},r}$ can be found by minimizing the distance between the actual and the theoretical reading results $E_{r-1},\ S_{r-1},\ C_{r-1}$ as

$$n_{\text{est},r} = \arg\min_{n_r} \left\{(\bar{E}_{r-1} - E_{r-1})^2 + (\bar{S}_{r-1} - S_{r-1})^2 + (\bar{C}_{r-1} - C_{r-1})^2\right\} - S_{r-1}, \tag{3}$$

where $\bar{E}_{r-1},\ \bar{S}_{r-1},\ \bar{C}_{r-1}$ are the expected values of $E_{r-1},\ S_{r-1},\ C_{r-1}$ respectively i.e., $\bar{E}_{r-1} = L_{r-1}(1-1/L_{r-1})^{n_r}$, $\bar{S}_{r-1} = n_r(1-1/L_{r-1})^{n_r-1}$ and $\bar{C}_{r-1} = L_{r-1} - \bar{E}_{r-1} - \bar{S}_{r-1}$. In Schoute method, the frame size is assumed to be chosen such that the number of tags responding to the reader in each slot is Poisson distributed with mean 1, which is valid if the frame size is equal to the number of undetected tags. Then, n_r is estimated by

$$n_{\text{est},r} = 2.39C_{r-1}. \tag{4}$$

On the other hand, the frame size can also be determined by by Q algorithm [14], which sets L_r to $2L_{r-1},\ L_{r-1}/2$, or L_{r-1} depending on the observed number of empty, singleton and collision slots

$$L_r = \begin{cases} 2L_{r-1} & \text{if } I_{r-1} \geq 1, \\ L_{r-1} & \text{if } I_{r-1} = 0, \\ L_{r-1}/2 & \text{if } I_{r-1} \leq -1, \end{cases} \tag{5}$$

where $I_{r-1} = \text{round}\left[(C_{r-1} - E_{r-1})\,k\right]$ and k is a constant $(0.1 \leq k \leq 0.5)$.

Figure 1 shows a simple example of the identification process with DFSA. The initial frame size is set to $L_1 = 2$ and the tags respond by sending their ID in the chosen time slots. After the first reading round, tags $1,\ 3$ and $2,\ 4$ cause two collisions since they transmit their ID at the same time and hence, $E_1 = 0,\ S_1 = 0$ and $C_1 = 2$. In the second reading round, by Log algorithm using Schoute estimate, the reader determines a new frame size $L_2 = 4$. In this case, all the tags are identified and $E_2 = 0,\ S_2 = 4,\ C_2 = 0$.

Table 1 Estimators of n with PFSA

Estimator	
PZE n_{e}	$e^{-(pn_{\mathrm{e}}/L)} = E/L$
PCE n_{c}	$1-(1+(pn_{\mathrm{c}}/L))e^{-(pn_{\mathrm{c}}/L)} = C/L$

2.2.2 PFSA

Probabilistic framed slotted ALOHA protocol deals with the tag set cardinality estimation problem using a fixed frame size i.e., $L_r = L$, which might be smaller than the total number of tags. Assuming each tag decides to contend in the frame with a probability p, two tag set cardinality estimators: Probabilistic Zero Estimator (PZE) and Probabilistic Collision Estimator (PCE) are derived using the empty and collision slots, which are described in Table 1, where n_{e} (n_{c}) is the number of tags estimated by PZE (PCE) estimator. The optimal probabilities corresponding to PZE and PCE are determined by minimizing the variance of the estimators.

3 Proposed Protocol: PDFSA

In this section, we propose the PDFSA protocol, which can be considered as an extension of DFSA and PFSA, to deal with the tag identification problem in the case where the total number of tags is large.

3.1 PDFSA

In the proposed protocol, the reader probes the tags by broadcasting the frame size and a parameter $p \in (0, 1]$ called transmission probability. Then, each tag contends in the frame with probability p, and if it decides to contend, randomly picks up one of the slots to respond. This reading process, where the frame size and the transmission probability are dynamically controlled, is repeated until all the tags are identified.

Suppose that in the rth reading round, using the frame size L_r and the transmission probability p_r, the reader obtains E_r empty, S_r singleton and C_r collision slots, where $L_r = E_r + S_r + C_r$. The CUE can be written as

$$\mathrm{CUE} = \frac{\bar{S}_r}{L_r} = \frac{n_r p_r}{L_r}\left(1 - \frac{p_r}{L_r}\right)^{n_r - 1}. \tag{6}$$

Setting the derivative of (6) with respect to p_r to be zero, we obtain

$$\frac{\partial(\mathrm{CUE})}{\partial p_r} = \frac{n_r}{L_r^2}\left(1 - \frac{p_r}{L_r}\right)^{n_r - 2}(L_r - p_r n_r) = 0,$$

or equivalently

$$L_r = p_r n_r. \tag{7}$$

We see that for a given L_r, if p_r is chosen to satisfy (7), the CUE and hence the number of tags detected in the frame is maximized. Also, with L_r and p_r satisfying (7), we have

$$\mathrm{CUE} = \left(1 - \frac{1}{n_r}\right)^{n_r - 1} \to \frac{1}{e} \quad (n_r \to \infty).$$

Algorithm 1 Log-based PDFSA

1: Initialize $L_r,\ p_r = 1$ for the first reading round ($r = 1$), and observe $E_1,\ S_1$ and C_1
2: **while** at least one tag is not identified **do**
3: $r = r + 1$
4: Find $n_{\text{est},r}$ and $L_r = 2^{\lfloor \log_2(n_{\text{est},r}) \rfloor}$ (if $n_{\text{est},r} < 1$ then $L_r = 1$)
5: $p_r = \min\left(1, \frac{L_r}{n_{\text{est},r}}\right)$
6: Broadcast L_r and p_r, and observe $E_r,\ S_r$ and C_r
7: **end while**

In order to satisfy (7), L_r has to be smaller than n_r, because p_r can only take the value in (0, 1]. On the other hand, from a viewpoint of the overhead required for each reading round, L_r should be set as large as possible in order to reduce the number of reading rounds. Thus, in the proposed protocol, L_r is determined by

$$L_r = 2^{\lfloor \log_2(n_{\text{est},r}) \rfloor}, \tag{8}$$

where $n_{\text{est},r}$ is the estimate of n_r, and $\lfloor X \rfloor$ rounds the value of X to the nearest integer less than or equal to X. Note that $n_{\text{est},r}$ can be found by some estimation methods such as Vogt method or Schoute method e.g.,

$$n_{\text{est},r} = \frac{S_{r-1} + 2.39C_{r-1}}{p_{r-1}} - S_{r-1}. \tag{9}$$

The probability p_r used for the rth reading round will be controlled by

$$p_r = \min\left(1, \frac{L_r}{n_{\text{est},r}}\right). \tag{10}$$

The proposed protocol is summarized in Algorithm 1, which is named Log-based PDFSA due to its similarity to the conventional Log algorithm for DFSA.

Another way to control the frame size L_r is to use the idea of conventional Q algorithm for DFSA. Specifically, L_r is controlled as follows

$$L_r = \begin{cases} 2L_{r-1} & \text{if } I_{r-1} \geq 1 \text{ and } n_{\text{est},r} \geq 2L_{r-1}, \\ L_{r-1} & \text{if } I_{r-1} \geq 0 \text{ and } L_{r-1} \leq n_{\text{est},r} < 2L_{r-1}, \\ \frac{L_{r-1}}{2} & \text{if } I_{r-1} \leq 0 \text{ and } \frac{L_{r-1}}{2} \leq n_{\text{est},r} < L_{r-1}, \\ \frac{L_{r-1}}{4} & \text{if } I_{r-1} \leq -1 \text{ and } n_{\text{est},r} < \frac{L_{r-1}}{2}, \end{cases} \tag{11}$$

In this case, the algorithm is called Q-based PDFSA.

4 Implementation of PDFSA Using Transmit Power Control

In PDFSA and PFSA protocols, tags need to be smart enough to cope with the transmission probability. Indeed, to implement PFSA for the tag set cardinality estimation, Phillips I-Code RFID smart tags [32], which can hash their IDs into the range $[1, \lceil L/p \rceil]$, where $\lceil X \rceil$ rounds the elements of X to the nearest integers greater than or equal to X, is used in [29]. Then, if the hashed value is smaller than L, the tag responds in the corresponding slot, otherwise it does not respond in the frame, thereby resulting in a transmission probability of $\frac{L}{L/p} = p$. However, since such a processing ability is not equipped in tags of common RFID systems [1], PFSA as well as PDFSA can not be directly applied to existing systems.

Here, we consider a practical way to implement PDFSA in common RFID systems, taking advantage of the fact that, in general, a tag responds to the reader only if its received signal power is strong enough for activation and signal decoding, or in other words, the tag's instantaneous Signal-to-Noise Ratio (SNR) is greater than the tag's sensitivity threshold. Indeed, an European Union tag operating at 868 MHz requires 50 microwatts to respond from a distance of about 3.25 m, under ideal conditions [19], and hence, transmit power control methods can be used to resolve RFID collision problems [22,31]. Specifically, in Ali et.al. [22], propose a novel approach for solving passive tag collision, namely the Power-based Distance Clustering (PDC) in which transmit power is controlled to cluster and identify the tags in distance ascending order from the reader. In [31], another method called transmission power control for collision arbitration (TPC-CA) is proposed to reduce redundant reader collisions. In our algorithm, the transmit power will be utilized to control the number of tags responding to the reader in each reading round such that the expected number of the contention tags is equal to the frame size. On the other hand, since the received SNR largely depends on the assumed channel model, we present transmit power control methods for a flat Rayleigh fading channel model and an AWGN channel model, separately.

4.1 PDFSA in Flat Rayleigh Fading Channel

The propagation model in this subsection will be assumed to be flat Rayleigh fading without effects of path-loss phenomenon. Specifically, the received signal model for tag i is described as

$$y_i = \sqrt{P} h_i s + v_i, \tag{12}$$

where s, P and h_i are the transmitted signal from the reader with zero mean and unit variance, the transmit power and the fading coefficient with $h_i \sim \mathcal{CN}(0, 1)$, respectively. v_i is an AWGN with $v_i \sim \mathcal{CN}(0, N_0)$. The model will be appropriate for indoor RFID applications where the channel is scattering rich and the transmission is considered to be short range. Tag i's instantaneous SNR for given h_i can be written as

$$\mathrm{SNR}_i^{\mathrm{Rayleigh}} = \frac{P h_i^2}{N_0}. \tag{13}$$

Then, suppose that tag i responds to the reader only if its instantaneous SNR is greater than a given threshold i.e., $\mathrm{SNR}_i^{\mathrm{Rayleigh}} > \gamma$, where γ is the tag's sensitivity threshold and is assumed to be the same for every tag. The probability that a tag participates in the contention can be derived as

$$\Pr\left(\mathrm{SNR}_i^{\mathrm{Rayleigh}} > \gamma\right) = \int_{\frac{\gamma N_0}{P}}^{\infty} e^{-x} dx = e^{-\frac{\gamma N_0}{P}}. \tag{14}$$

Hence, the transmit power P can be used to control the transmission probability as $p = e^{-\frac{\gamma N_0}{P}}$.

Before the rth reading round, suppose that the observations E_{r-1}, S_{r-1} and C_{r-1} are available so that the total number of undetected tags can be estimated. For example, if we employ Schoute method in (9), we have

$$n_{\mathrm{est},r} = (S_{r-1} + 2.39 C_{r-1}) e^{\frac{\gamma N_0}{P_{r-1}}} - S_{r-1}, \tag{15}$$

Algorithm 2 TPC/Rayleigh

1: Initialize $L_r,\ \gamma,\ P_r = P_{\max}$ for the first reading round ($r = 1$), and observe $E_1,\ S_1$ and C_1
2: **while** at least one tag is not identified **do**
3: $\quad r = r + 1$
4: $\quad$ Find $n_{\text{est},r}$ and $L_r = 2^{\lfloor \log_2(n_{\text{est},r}) \rfloor}$
5: $\quad P_r = \frac{\gamma N_0}{\log\left(\frac{n_{\text{est},r}}{L_r}\right)}$ (if $P_r > P_{\max}$ then $P_r = P_{\max}$)
6: $\quad$ Broadcast L_r using P_r, and observe $E_r,\ S_r$ and C_r
7: **end while**

where P_{r-1} is the transmit power in the $(r-1)$th reading round. Then, the frame size in the rth reading round L_r can be determined by using (8). Finally, the transmit power is obtained by

$$P_r = \frac{\gamma N_0}{\log\left(\frac{n_{\text{est},r}}{L_r}\right)}. \tag{16}$$

Note that there is a restriction on the maximum transmit power in general, and P_r in (16) might be greater than the maximum value $P_{\max}$. Thus, if $P_r > P_{\max}$, then we set $P_r = P_{\max}$. Also, note that we set $P_1 = P_{\max}$ so that as many tags as possible respond to the request to obtain the information of the total number of tags in the range. The algorithm is summarized in Algorithm 2, which we call Transmit Power Control in Rayleigh fading channel (TPC/Rayleigh). In addition, the frame size can also be determined by using (11).

4.2 PDFSA in AWGN Channel

In this subsection, all the tags will be assumed to be uniformly distributed in a circle with radius R_1 centered at the reader. The received signal model for tag i in AWGN channel is described as

$$y_i = \sqrt{P l_i^{-\eta}}\, s + v_i, \tag{17}$$

where η is the path-loss exponent and l_i is the distance from tag i to the reader. The tag i's SNR can thus be given by

$$\text{SNR}_i^{\text{AWGN}} = \frac{P l_i^{-\eta}}{N_0}. \tag{18}$$

We suppose that tag i is in the range covered by the reader with transmit power P if $\text{SNR}_i^{\text{AWGN}}$ is greater than or equal to the threshold γ. In other words, if $P \geq N_0 l_i{}^{\eta} \gamma$, tag i responds to the reader, otherwise, it does not. Hence, the transmit power can be used to control the number of tags to respond. We denote A_r the area covered by P_r, which is the transmit power of the rth reading round, where all the tags within A_r respond, and $n_{\text{est}}^{\text{A}_r}$ the estimated number of undetected tags in A_r. $n_{\text{est}}^{\text{A}_r}$ can be obtained by any estimation method such as Vogt method in (3) or Schoute method in (4) using observations $E_r,\ S_r$ and C_r.

We now describe how to control the frame size and the transmit power in each reading round. In particular, the initial transmit power is set to the maximum value $P_1 = N_0 R_1^{\eta} \gamma := P_{\max}$, which covers the circle with radius R_1 so that all the tags respond. The reader observes $E_1,\ S_1,\ C_1$, and hence the total number of undetected tags $n_{\text{est},2}$ is estimated where $n_{\text{est}}^{\text{A}_1} = n_{\text{est},2}$ after the 1st reading round.

In the 2nd reading round, the frame size is determined by $L_2 = 2^{\lfloor \log_2(n_{\text{est},2}) \rfloor}$. To obtain the optimal CUE, the transmit power P_2 is controlled so that the expected number of tags

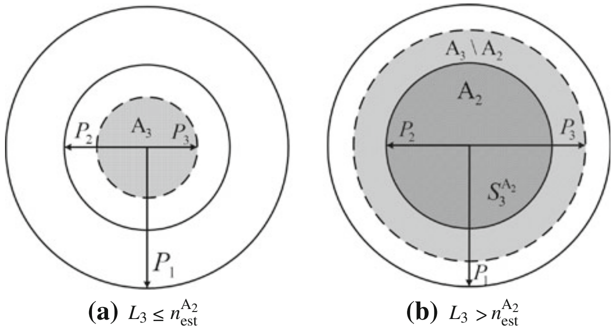


Fig. 2 Transmit power control in AWGN channel-The 3rd reading round

responding to the reader is equal to the frame size L_2. On the other hand, since $P_1 = N_0 R_1^{\eta} \gamma$, all tags are detected with the same probability in the 1st reading round regardless of the tags' positions. Thus, the distribution of undetected tags before the 2nd reading round is also uniform, where the estimated number of undetected tags in A_1 ($n_{\text{est}}^{A_1}$) is $n_{\text{est},2}$. In other words, denoting R_2 the communication radius in the 2nd reading round, we have $L_2/n_{\text{est},2} = R_2^2/R_1^2$. Hence, from (18), we obtain $P_2 = P_1 \left(L_2/n_{\text{est},2}\right)^{\eta/2}$. After observing E_2, S_2 and C_2, $n_{\text{est}}^{A_2}$ is estimated. Then, the total number of undetected tags in A_1 before the 3rd reading round is estimated as $n_{\text{est},3} = \left(n_{\text{est}}^{A_2} + S_2\right)(P_1/P_2)^{2/\eta} - S_2$ since $(P_2/P_1)^{2/\eta}$ is the ratio of the number of undetected tags between A_2 and A_1. Note that we only use the latest observations (E_2, S_2, C_2) for the estimation of the number of undetected tags for simplicity, although it could be possible to improve the estimation by using all the observations obtained. At the end of the 2nd reading round, the estimated number of undetected tags in A_1 is updated by $n_{\text{est}}^{A_1} = n_{\text{est},3}$.

In the 3rd reading round, the frame size is determined as $L_3 = 2^{\lfloor \log_2(n_{\text{est},3}) \rfloor}$, and the transmit power P_3 is also controlled so that the expected number of undetected tags in the communication range is equal to L_3. We separate this situation into two cases corresponding to the value of L_3 as follows

- $L_3 \le n_{\text{est}}^{A_2}$:
  In this case, P_3 will be set as $P_3 \le P_2$, as shown in Fig. 1a. Since the tag distribution in A_2, and hence A_3, is uniform, P_3 can be determined as $P_3 = \left(L_3/n_{\text{est}}^{A_2}\right)^{\eta/2} P_2$. Besides, the estimated number of undetected tags outside A_2 is $n_{\text{est}}^{A_1} - n_{\text{est}}^{A_2}$, while the number of undetected tags in A_2 is re-estimated by $\left(n_{\text{est}}^{A_3} + S_3\right)(P_2/P_3)^{2/\eta} - S_3$. Hence, the estimated total number of undetected tags before the 4$^{\text{th}}$ reading round is $n_{\text{est},4} = n_{\text{est}}^{A_1} - n_{\text{est}}^{A_2} + \left(n_{\text{est}}^{A_3} + S_3\right)(P_2/P_3)^{2/\eta} - S_3$. The numbers of undetected tags in A_1 and A_2 are updated as $n_{\text{est},4}$ and $n_{\text{est}}^{A_2} - S_3$, respectively.
- $L_3 > n_{\text{est}}^{A_2}$:
  P_3 will be set to $P_2 < P_3 \le P_1$ as shown in Fig. 2b. Let $A_x \setminus A_y$ denote the area inside the circle covered by P_x but outside the circle covered by P_y. We can see that the undetected tag density in $A_1 \setminus A_2$ is uniform, while the numbers of undetected tags in $A_1 \setminus A_2$ and $A_3 \setminus A_2$ are $n_{\text{est}}^{A_1} - n_{\text{est}}^{A_2}$ and $L_3 - n_{\text{est}}^{A_2}$, respectively. Thus, P_3 and $n_{\text{est},4}$ can be obtained as

Algorithm 3 TPC/AWGN

1: Initialize $L_r,\ \gamma,\ P_r = N_0 R_0^{\eta}\gamma,\ \eta = 3$ for the first reading round ($r = 1$), observe $E_1,\ S_1$ and C_1 and determine $n_{\text{est},2} = n_{\text{est}}^{\text{A}_1}$
2: **while** at least one tag is not identified **do**
3: $r = r + 1$ and $L_r = 2^{\lfloor \log_2 (n_{\text{est},r}) \rfloor}$
4: Find $P_u,\ P_v$ and $P_r = \left(P_u^{\frac{2}{\eta}} + \frac{\left(L_r - n_{\text{est}}^{\text{A}_u}\right)\left(P_v^{\frac{2}{\eta}} - P_u^{\frac{2}{\eta}}\right)}{n_{\text{est}}^{\text{A}_v} - n_{\text{est}}^{\text{A}_u}} \right)^{\frac{\eta}{2}}$
5: Broadcast L_r using P_r, and observe $E_r,\ S_r$ and C_r ($r \geq 2$)
6: $n_{\text{est},r+1} = n_{\text{est}}^{\text{A}_1} - n_{\text{est}}^{\text{A}_v} + n_{\text{est}}^{\text{A}_u} - S_r + \frac{\left(n_{\text{est}}^{\text{A}_r} + S_r - n_{\text{est}}^{\text{A}_u}\right)\left(P_v^{\frac{2}{\eta}} - P_u^{\frac{2}{\eta}}\right)}{P_r^{\frac{2}{\eta}} - P_u^{\frac{2}{\eta}}}$
7: Update $n_{\text{est}}^{\text{A}_1}, \ldots, n_{\text{est}}^{\text{A}_{r-1}}$
8: **end while**

$$P_3 = \left(P_2^{\frac{2}{\eta}} + \frac{\left(L_3 - n_{\text{est}}^{\text{A}_2}\right)\left(P_1^{\frac{2}{\eta}} - P_2^{\frac{2}{\eta}}\right)}{\left(n_{\text{est}}^{\text{A}_1} - n_{\text{est}}^{\text{A}_2}\right)} \right)^{\frac{\eta}{2}}, \tag{19}$$

and

$$n_{\text{est},4} = n_{\text{est}}^{\text{A}_2} - S_3 + \frac{\left(n_{\text{est}}^{\text{A}_3} + S_3 - n_{\text{est}}^{\text{A}_2}\right)\left(P_1^{\frac{2}{\eta}} - P_2^{\frac{2}{\eta}}\right)}{\left(P_3^{\frac{2}{\eta}} - P_2^{\frac{2}{\eta}}\right)}. \tag{20}$$

On the other hand, since all tags in A_3 are detected in the 3rd reading round with the same probability, the numbers of undetected tags in $\text{A}_1,\ \text{A}_2$ are updated as $n_{\text{est},4},\ n_{\text{est}}^{\text{A}_2} - S_3 n_{\text{est}}^{\text{A}_2}/L_3$, respectively.

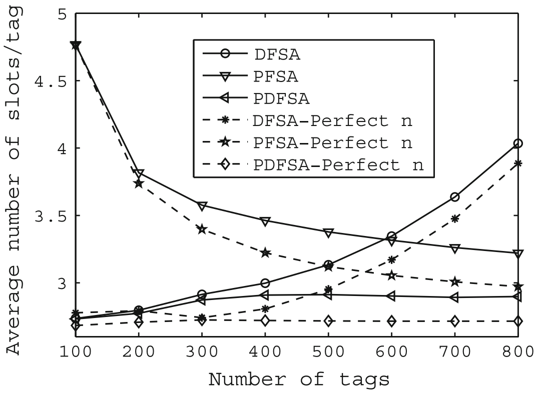
We now generalize the proposed method to the rth reading round by explaining how to control the frame size L_r and the transmit power P_r. In particular, after the $(r-1)$th reading rounds, the estimated total number of undetected tags $n_{\text{est},r}$ is available, so the frame size L_r is determined by $L_r = 2^{\lfloor \log_2 (n_{\text{est},r}) \rfloor}$. Then, for given L_r, we find the largest A_u and the smallest A_v such that $n_{\text{est}}^{\text{A}_u} < L_r \leq n_{\text{est}}^{\text{A}_v}$ (if no such A_u exists, we set $P_u = 0$ and $\text{A}_u = \emptyset$). It implies that $P_u < P_r \leq P_v \leq P_1$. As the undetected tag distribution in $\text{A}_v \backslash \text{A}_u$ is uniform, P_r and $n_{\text{est},\ r+1}$ are determined by

$$P_r = \left(P_u^{\frac{2}{\eta}} + \frac{\left(L_r - n_{\text{est}}^{\text{A}_u}\right)\left(P_v^{\frac{2}{\eta}} - P_u^{\frac{2}{\eta}}\right)}{n_{\text{est}}^{\text{A}_v} - n_{\text{est}}^{\text{A}_u}} \right)^{\frac{\eta}{2}}, \tag{21}$$

and

$$n_{\text{est},r+1} = n_{\text{est}}^{\text{A}_1} - n_{\text{est}}^{\text{A}_v} + n_{\text{est}}^{\text{A}_u} - S_r + \frac{\left(n_{\text{est}}^{\text{A}_r} + S_r - n_{\text{est}}^{\text{A}_u}\right)\left(P_v^{\frac{2}{\eta}} - P_u^{\frac{2}{\eta}}\right)}{P_r^{\frac{2}{\eta}} - P_u^{\frac{2}{\eta}}}. \tag{22}$$

Fig. 3 Average number of slots/tag-Log based algorithm



On the other hand, since all tags in A_r are detected in the rth reading round with the same probability, the numbers of undetected tags in A_1, A_b for all $P_v \leq P_b < P_1$, and A_g for all $P_g \leq P_u$ are updated as $n_{\text{est},r+1}$, $n_{\text{est}}^{A_b} - S_r$, and $n_{\text{est}}^{A_g} - S_r n_{\text{est}}^{A_g}/L_r$, respectively.

Note that, as mentioned before, the frame size in this algorithm can also be found by (11), while the tag set cardinality can be estimated by any estimation method. The proposed protocol is summarized in Algorithm 3, which we call Transmit Power Control in AWGN channel (TPC/AWGN).

5 Simulation Results

In this section, the performance of the proposed method under different system parameters will be evaluated and compared with that of the conventional DFSA and PFSA via computer simulations. The frame size in PFSA can be an arbitrary constant during the identification process, however, it will be set to the initial frame size of the other methods. On the other hand, the total number of tags is assumed to range from 100 to 800, while the initial and the maximal frame sizes of the proposed method and DFSA are set to 128 and 256, respectively. In order to estimate the tag set cardinality, Vogt method will be utilized for the 1st reading round, while Schoute method is used from the 2nd reading round for simplicity. This is because we cannot assume $L_r = n_r$ or $L_r = p_r n_r$, which are required for Schoute method, in the first reading round. The simulation results are obtained by Monte Carlo method with 10^5 runs.

In Fig. 3, we plot the average number of slots taken per tag to identify all the tags versus number of tags of DFSA with Log algorithm, PFSA and Log-based PDFSA. The performance of all the methods when n is known (DFSA-Perfect n, PFSA-Perfect n, PDFSA-Perfect n) is also presented. We can see that, when n is large ($n \geq 600$), the performance of PFSA is better than that of DFSA because p is utilized efficiently to reduce the collisions. However, for smaller values of n, since $0 < p \leq 1$, PFSA takes more slots to detect a tag than DFSA. On the other hand, PDFSA, by dynamically controlling both L and p to obtain the optimal CUE in every reading round, outperforms the conventional methods. Also, PDFSA-Perfect n outperforms PFSA-Perfect n and DFSA-Perfect n, which implies that PDFSA shows better achievable performance than PFSA and DFSA.

The performance of DFSA with Q algorithm and Q-based PDFSA is also evaluated and is compared with that of PFSA in Fig. 4. Similar to the previous case, the proposed PDFSA outperforms the conventional methods.Note that the performance of DFSA-Perfect n with Q

Fig. 4 Average number of slots/tag-Q based algorithm

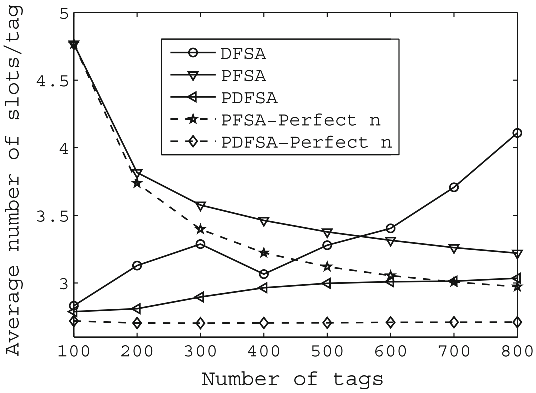
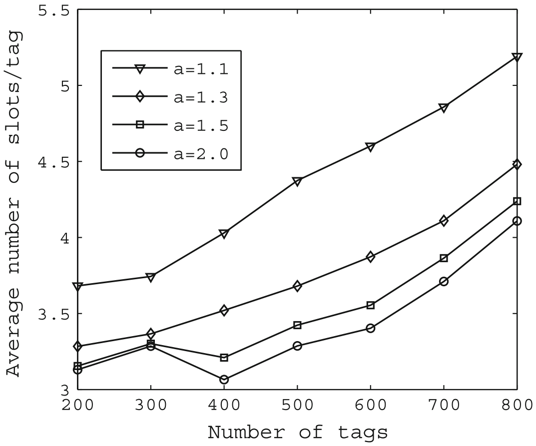


Fig. 5 Average number of slots/tag-Q based DFSA with different cases of granularity



algorithm is not discussed in this paper since Q algorithm does not directly use the estimated number of tags to vary the frame size. Also, the average number of slots/tag of Q-based DFSA is dropped abruptly at $n = 400$ because of the granularity of the frame size in the Q algorithm. Figure 5 shows the performance of Q-based DFSA with different cases of the granularity i.e., the frame size in the next reading round is selected only from one of three options i.e., L, L/a and aL with different values of a predefined constant a, where L is the frame size in the current reading round. We can see that, for small values of $a (a < 1.5)$, the average number of tags no longer drops abruptly.

We now re-simulate the performance of all the methods without limitation of the maximal frame size i.e., it is under the form 2^Q but with $Q \in \mathbb{N}$, and the results are shown in Figs. 6 and 7. We can see that the performance of PFSA is the same as the previous cases because the frame size is constant. On the other hand, the performance of DFSA is improved for large values of n because the number of collisions is reduced. In both figures, PDFSA achieves the best performance among the evaluated methods. However, from Fig. 6, we can see that the performance of DFSA-Perfect n is almost the same as that of PDFSA-Perfect n, while PDFSA largely outperforms DFSA for the case without ideal knowledge on n. This is because PDFSA can always set the frame size to be equal to the number of tags participating in the contention by using the probability, which is required by Schoute method for accurate estimation, while this cannot be achieved necessarily with DFSA due to the limitation of the frame size to 2^Q.

Fig. 6 Average number of slots/tag-Log based algorithm (without limitation of maximal frame size)

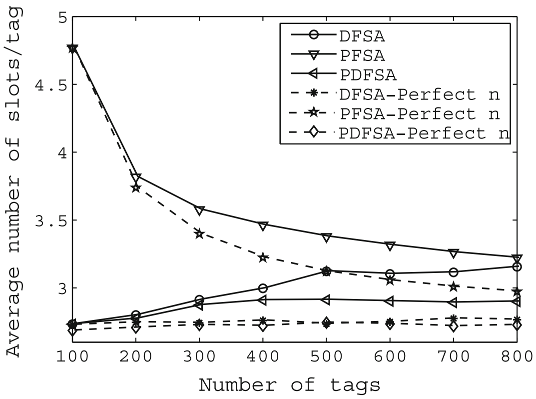


Fig. 7 Average number of slots/tag-Q based algorithm (without limitation of maximal frame size)

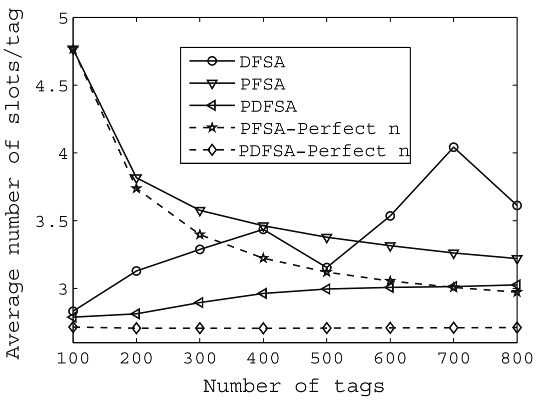
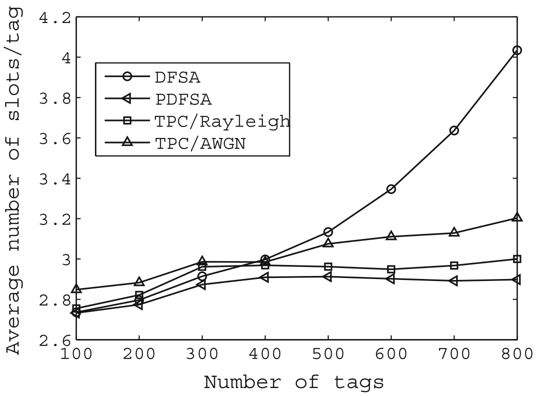


Fig. 8 Transmit power control-Log based algorithm



Thus, the improved accuracy of the tag set cardinality estimation will be the major cause of the performance gain of the proposed PDFSA against DFSA in this case.

The performance of TPC/Rayleigh and TPC/AWGN is compared with that of DFSA and PDFSA in Figs. 8 and 9. The maximum transmit power in TPC/Rayleigh is assumed to be equal to that in TPC/AWGN. We can see that TPC/Rayleigh outperforms DFSA regardless

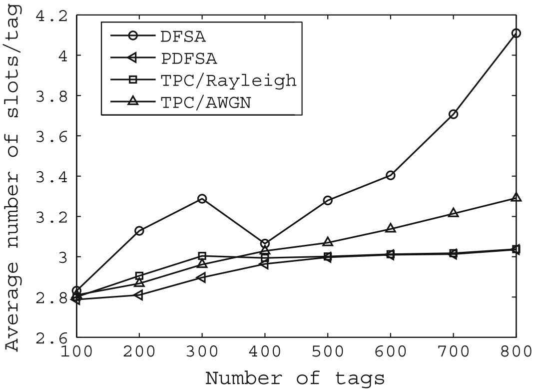


Fig. 9 Transmit power control-Q based algorithm

of the ways determining the frame size, and the performance of TPC/Rayleigh can be comparable to that of PDFSA. The degradation of the performance of TPC/Rayleigh from that of PDFSA is mainly due to the limitation of the maximum transmit power, which results in the limitation on the probability. In TPC/AWGN, not only the total number of undetected tags in the whole range but also that in each region has to be estimated. Hence, the performance of TPC/AWGN is worse than that of TPC/Rayleigh especially when the total number of tags is large, while the performance is still far better than that of the conventional DFSA.

6 Conclusion

In this paper, we have proposed an efficient RFID tag identification protocol named PDFSA to deal with the identification problem with a large number of tags while the choice of the frame size is constrained. In the proposed method, the transmission probability that each tag participates in the contention and the frame size are dynamically controlled to obtain the optimal CUE. The protocol is also studied under wireless communication scenarios such as AWGN and flat Rayleigh fading channels, where practical ways of controlling the transmission probability are proposed by means of the transmit power control. The proposed methods are evaluated under different system parameters via computer simulations, and compared to the performance of conventional methods. From all the results, it can be concluded that the proposed approach of controlling both frame size and probability (or transmit power) is effective to achieve efficient RFID tag identification.

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