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Bayesian estimation in dynamic framed slotted ALOHA algorithm for RFID system

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ABSTRACT

This paper develops a novel dynamic framed slotted ALOHA (DFSA) algorithm based on Bayesian estimation to improve the throughput of the radio frequency identification (RFID) system. At first, four types of anti-collision algorithms for tag identification are analyzed. Then, the proposed DFSA based on Bayesian estimation is deduced and introduced. Compared with the conventional DFSA algorithms, this algorithm takes advantage of the evidence in previous frames as the a priori information of the current frame which can end up with more precise estimation of tag number and rational frame length adjustment. Finally, the common simulation tool from Matlab is used to demonstrate the effectiveness of the proposed new algorithm for the average throughput improvements of the RFID system.

1. Introduction

In recent years, RFID became a booming non-contact automatic identification technology. A typical RFID system consists of tags, a reader as well as data processing parts. Each tag has its own ID called unique ID (UID) which is fixed at the manufacturing stage [1]. Each UID will be transmitted to the reader by itself when the tag is in the operational range of the reader. If the tag is identified successfully, the reader will send commands to this specific tag. After this, the communication process between tags and reader finishes. However, under many application conditions, such as in a warehouse, a supermarket or at a motorway tollbooth, there could be a large number of tags within the operational range of reader at the same time [2]. When two or more tags communicate with the reader simultaneously, signals will interfere with each other and the reader will detect a collision. The collision will reduce the identification efficiency of the RFID system dramatically. For general collision problems in a wireless communication system, the solutions can be grouped into four types: SDMA (space division multiple access), FDMA (frequency division multiple access), CDMA (code division multiple access) and TDMA (time division multiple access) [3]. But unfortunately, since the tags are passive devices with very limited power, most anti-collision algorithms cannot be implemented in an RFID system directly because of their high computational complexities. One of the critical challenges for RFID systems is maximizing the tag identification speed while maintaining low computational complexity [4].

Many earlier research works focused on improving the tag identification speed by reducing the collision probability. These anti-collision algorithms can be categorized as tree-based algorithms and ALOHA-based algorithms [5–7]. Compared with ALOHA-based algorithms, tree-based algorithms require more hardware cost [8]. Moreover, they are not suitable in situations that demand security [9,10]. Therefore, the most concerned strategy for identification efficiency improvement of the RFID system is the ALOHA protocol.

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The ALOHA protocol was first proposed by Abramson in 1970, and it has been applied in the packet switching of computer networks widely [11]. However, in the ALOHA protocol, the theoretical maximum channel throughput is only 18.4% and it seems to be quite low [12]. In order to improve the throughput, the slotted ALOHA protocol was developed in some research works. For the slotted ALOHA protocol, the channel is divided into slots and only one packet is transmitted in each slot. The theoretical maximum throughput is boosted up to 36.8% in slotted ALOHA. But its disadvantage is the low throughput under heavy load conditions. DFSA is an advanced type of framed slotted ALOHA (FSA). It adjusts the frame length dynamically according to the estimation of the backlog, and it obtained a relatively higher throughput than slotted ALOHA under heavy load conditions [13].

Due to its higher throughput under high load conditions and better dynamic features than normal FSA, DFSA was widely applied in RFID system to reduce the collisions during the communication process between the tags and reader. Vogt introduced an error-distance estimation scheme which estimates the tag quantity that minimizes the error between the observed number of empty, singly-occupied, collision slots and their expected values [14]. He also used the Markov process to model the read process and suggested a set of dynamic frame lengths in the read process. Through the use of the Markov model, he computed a lower bound of the number of reading steps needed to identify all tags. The simulation results proved that the error-distance algorithm estimates the tag quantity more accurately than the lower bound algorithm. He showcased the performance of the algorithm in the commercially available RFID system, the I-code, which was developed by Philips Semiconductors. However, the frame length in the I-code system must be the exponential power of 2. This restriction limits the maximum throughput of the system.

The maximum throughput of the RFID system can be reached when the number of slots in a frame equals the number of unidentified tags [15]. Cha improved the Schoute algorithm and applied it in RFID systems for the first time [16]. He used slots with collision in the system and the ratio of the number of collided slots to determine the optimal frame size. The performances of the proposed DFSA algorithm with that of conventional FSA algorithm are compared using OPNET simulation. The proposed DFSA algorithms show better performance than FSA. However, the algorithm only made use of the collision slots which generate large estimation errors in case collided tags are not uniformly distributed in each collision slot. Lee proposed an enhanced dynamic framed slotted ALOHA algorithm [17]. The tags are divided into groups when the tag quantity increases sharply. Only one group responds to the reader each time. But it is impossible to group the tags accurately since the tag ID is unknown to the reader side. In [18], the author proposed a new transmission control scheme for fast RFID object identification. The scheme optimized traditional Bayesian broadcast theory proposed in [19] and made it fit the special requirement of RFID systems. But the initial tag quantity distribution is not deduced and lack of practical evidence limits its application prospects in RFID systems. Chen proposed a method for tag estimate by searching maximum a posteriori probability [20]. The author derived the exact a posteriori probability distribution and proposed a decision rule for tag estimate, named the maximum a posteriori probability rule. A major concern is the tag quantity range over which the minimal distance or the maximum probability needs to be searched. If the range is wide, the estimated computational complexity will be high.

This paper presents a DFSA algorithm based on Bayesian estimation. Unlike the conventional DFSA algorithms, this novel strategy not only takes full advantage of the slot information collected by the reader in current frame, but also makes use of previous frame information as anterior information as it dynamically adjusts the frame size according to Bayesian theory. The optimization of the algorithm is also discussed. Our numerical results show that the proposed strategy can estimate the tag quantity more precisely and improve the throughput of the RFID system compared with other existing DFSA algorithms. Therefore, the reader which applies this proposed novel algorithm will identify more tags in a fixed time than conventional RFID readers.

This paper is organized as follows. Section 2 presents the basic dynamic framed slotted ALOHA algorithm and the RFID system model. Section 3 proposes the Bayesian tag estimate method. Section 4 shows simulation results on the performance of the proposed algorithm. Section 5 draws conclusions.

2. Dynamic framed slotted ALOHA algorithm

In RFID systems, the reader communicates with the tags through a wireless communication channel. At the beginning of the DFSA algorithm, the reader initializes the communication process and broadcasts a request command to all tags in the interrogation zone. The request command contains critical information such as the frame length. As a frame is composed of several slots with equal length, the frame length represents the total number of slots in a frame. The tag consists of an antenna and a chip with a built-in counter and a pseudo random number generator (PRNG). When the tag receives the request command, the PRNG will generate a pseudo random number less than or equal to the frame length. Then the counter starts counting down from this pseudo random number. It will automatically subtract one if a slot passes. When the counter value reaches zero, the tag will send its ID or some specific information to the reader. This process appears like each tag randomly selects a slot in the frame and begins to transmit information at the start of that slot.

There are three possibilities for a given slot: empty, successful or collision. The communication channel will be empty if no tag transmits information, a successful transmission means exactly one tag chooses this time slot for data transfer, while a collision means two or more tags occupy the same time slot, in which case the communication channel suffers from this collision and no tag can be read. Let E, S, C be the number of empty, successful and collision slots in a frame with the frame

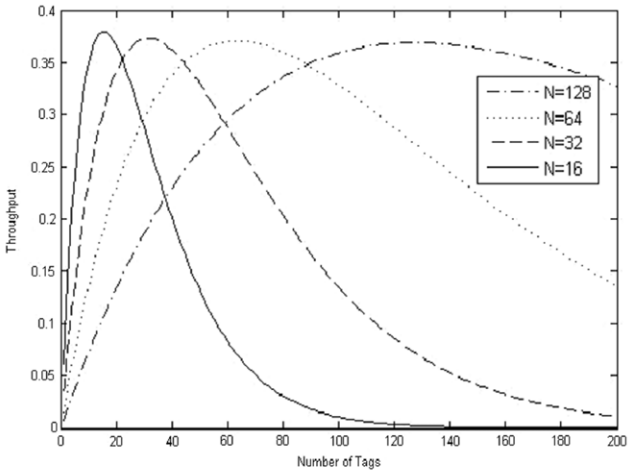

Fig. 1. Throughput of RFID system vs number of tags.

length N, then the following equation can be obtained: $N = E + S + C$. For a given number of tags, the values of E, S, C vary as the frame length N is dynamically adjusted. The system throughput will be higher if more successful slots are observed.

Assume that there are n unidentified tags and the frame contains N slots, and that each tag randomly selects a slot of the frame with the same probability $1/N$. The probability that k tags simultaneously transmit information in one slot is:

$$P(k) = \binom{n}{k}\left(\frac{1}{N}\right)^k\left(1-\frac{1}{N}\right)^{n-k}. \tag{1}$$

From Eq. (1), the expectation of identified tags after one frame circle can be obtained as follows:

$$N \cdot P(1) = N \cdot \binom{n}{1}\left(\frac{1}{N}\right)^1\left(1-\frac{1}{N}\right)^{n-1} = \binom{n}{1}\left(1-\frac{1}{N}\right)^{n-1}. \tag{2}$$

Generally, the throughput of the RFID with N slots and n identified tags is defined as:

$$T(n,\ N) = \frac{tags_{identified}}{N} = P(1) = \binom{n}{1}\left(\frac{1}{N}\right)^1\left(1-\frac{1}{N}\right)^{n-1}. \tag{3}$$

The maximum throughput occurs at $\frac{\partial T}{\partial n} = 0$. According to (2) and (3), this condition can be expressed as:

$$n = \frac{1}{\ln \frac{N}{N-1}}. \tag{4}$$

In practice, the frame length is always greater than 1. Therefore $n \approx N$ can be obtained from (4) when $N \gg 1$. Accordingly, the maximum throughput 36.8% can be calculated form (3). Fig. 1 shows the throughput of the RFID system as a function of the number of tags with different frame length. When the number of tags equals the frame length, the throughput reaches the maximum value approximately equal to 36.8% as calculated theoretically.

In order to maximize the throughput, the reader must set the frame length equal to the number of unidentified tags. Therefore, the key point of the DFSA algorithm is to calculate the number of unidentified tags. After a frame, the reader collects the number of empty, successful and collision slots. Then it will estimate the number of unidentified tags according to the collected information, and dynamically adjust the frame length in the next frame. The communication process will be finished if there is no collision slot in a frame.

The DFSA algorithm has been applied in RFID systems to ensure high system throughput, but the existing estimation methods still need improvement for their estimation accuracy.

There are mainly four estimation methods:

(1) Vogt algorithm. The estimation equation is shown as (5), where a_0, a_1, $a_{\geq 2}$ are the expected values of empty, successful and collision slots in a frame. The value n which minimizes the distance of the two vectors will be the estimation of unidentified tags.

$$\varepsilon_{vd} = \left|\begin{pmatrix} a_0 \\ a_1 \\ a_{\geq 2} \end{pmatrix} - \begin{pmatrix} E \\ S \\ C \end{pmatrix}\right|_{\min}. \tag{5}$$

(2) Lowbound algorithm. Since there are more than two tags in a collision slot, the minimum number of unidentified tags in a frame are $2C$. Take into account that there are S successful tags, the total number of tags will be $S + 2C$.

(3) Schoute algorithm. Assuming that the throughput reaches the maximum point, the expected number of tags contained in each collision slot can be calculated by Eq. (6). P_{succ} and P_{coll} represent the probability of successful and collisions in a single slot respectively. The tag number is estimated by $S + 2.39C$.

$$C_{tags} = \frac{1}{C_{rate}} = \lim_{n\to\infty} \frac{1 - P_{succ}}{P_{coll}} = 2.3922. \tag{6}$$

(4) Max probability algorithm. The probability that there are E empty, S successful and C collision slots in a frame is shown as (7). The algorithm chooses the number $\hat{n}$, which maximizes the probability $P(E, S, C)$, as the estimation of n.

$$P(E, S, C) = \frac{L!}{E!S!C!} P_e^E P_s^S P_c^C. \tag{7}$$

3. Bayesian estimation in dynamic framed slotted ALOHA algorithm

The slot information collected by the reader at the end of a frame must have some random features because each tag selects a slot in the frame randomly. The values of E, S, C in two frames may be different even if both frames have the same frame length N and number of tags n. Therefore the estimated number of tags should be treated as a random variable with certain probability distribution rather than as a fixed constant.

Although a reader may have already used several frames in its effort to identify all tags at the time when the next frame length is to be determined, the information it collected from the prior frame may not contain enough information for it to make a good estimation of the next frame length. The Bayesian method is very suitable for estimation under the condition that there are few observation samples [21,22]. It takes advantage of the evidence in previous frames as the a priori information of the current frame, which makes the Bayesian method more effective in collecting observations than previous methods. Moreover, the Bayesian could also be used for the tag quantity estimate. The Bayesian method is very suitable for updating the probability distribution of tag quantity, a rational estimation method is presented as (8) by using the expectation of tag number probability distribution.

$$n = E(n) = \sum_{n_{\min}}^{n_{\max}} nP(n). \tag{8}$$

Accordingly, a DFSA algorithm based on Bayesian estimation is proposed. The proposed algorithm procedure can be divided into the following five steps:

Step 1. Setting the initial frame length and sending the request command to tags asking for their information.

Step 2. Initializing the probability distribution function of the tag number.

Step 3. Updating the probability distribution of the tag quantity according to E, S, C values collected at the end of the frame.

Step 4. Computing the expected value of tag number by using the probability distribution function, then adjusting the length of the next frame.

Step 5. Repeating Step 3 if collision occurs, terminating otherwise (since all the tags would have been identified successfully).

The details of steps 1 to 4 are explained in the following.

Step 1. The determination of the initial frame length

The throughput T of N slots and n tags can be obtained from Eq. (3). Then optimal initial frame length can be deduced by maximizing the expectation of the system throughput:

$$E(S) = \sum_{n=0}^{n_{\max}} T(n, N)P(n). \tag{9}$$

The initial frame length will affect the performance of the algorithm. Large frame length will increase the number of empty slots, while small frame length will generate more collisions. In fact, it is difficult to get the experience probability distribution of the tag number because the application situation is complex. In this paper, a fixed initial frame length is used in order to compare with other algorithms.

Step 2. The initialization of the probability distribution of the tag number

As no experience probability distribution of the tag number is adopted, the tag number is supposed to be uniformly distributed. According to the E, S, C values collected by the reader, the lower bound is set to $S + 2C$. Theoretically, the higher bound will be set to the maximum n which makes $P(E \cap S \mid n) \geq 10^{-5}$ because the tag number outside this bound will make no contribution to the expectation. However, in RFID system, the higher bound is always restrained by the reader rather than calculated theoretically.

Step 3. Tag number estimation based on Bayesian theory

The reader estimates the tag number according to the number of empty, successful and collision slots. Let Idenotes the evidence of E, S, C, according to the Bayesian theory, then

$$P(n \mid I) = \frac{P(I \cap n)}{P(I)} = \frac{P(I \mid n)P(n)}{P(I)}. \tag{10}$$

In a frame, $P(I)$ can be regard as a constant and will be eliminated after the expectation of tag number is calculated. Since $E + S + C = N$, $P(I \mid n)$ can be expressed as

$$P(I \mid n) = P(E \cap S \cap C \mid n) = P(E \cap S \mid n). \tag{11}$$

Then

$$\begin{aligned} P(E \cap S \mid n) &= \frac{P(S \cap n)}{P(n)} \cdot \frac{P(E \cap S \cap n)}{P(S \cap n)} \\ &= P(S \mid n) \cdot P(E \mid S \cap n). \end{aligned} \tag{12}$$

Firstly, calculate the probability $P(S \mid n)$ that S success slots observed in a frame. Randomly choose S slots in N slots and S tags in n tags, and each slot is filled with only one tag. Since no new tags have been identified until now, the $n - S$ tags are chosen to fill $N - S$ slots. Therefore,

$$P(S|n) = \frac{\binom{N}{S} \left(\prod_{y=0}^{S-1} \binom{n-y}{1} \right) f(N-S, n-S)}{N^n}. \tag{13}$$

Here, $f(N - S, n - S)$ stands for the probability that $N - S$ slots are filled, empty or collision by these $n - S$ tags. The probability function $f(N, n)$ is

$$f(N, n) = N^n + \sum_{k=1}^{n} (-1)^k \binom{n}{k} \prod_{j=0}^{k-1} \binom{N-j}{1} (N-k)^{n-k}. \tag{14}$$

Secondly, based on S success slots the probability $P(E \mid S \cap n)$ that E empty slots are observed can be calculated. The remaining $n - S$ tags are distributed into C slots and each slot contains at least two tags, while the remaining E slots are empty. Therefore $P(E \mid S \cap n)$ is given by

$$P(E \mid S \cap n) = \frac{\sum_{k=0}^{C} (-1)^k \binom{E+k}{E} \binom{N-S}{E+k} f(N-S-E-k, n-S)}{f(N-S, n-S)}. \tag{15}$$

From Eqs. (12), (13) and (15), $P(E \cap S \mid n)$ can be calculated.

Step 4. The length adjustment of the next frame

Let S be the number of tags successfully identified after the tth frame, the tag number distribution probability in the $(t + 1)$th frame is then given by

$$P_{t+1}(n - S) = P_t(n \mid I). \tag{16}$$

where $P_t(n \mid I)$denotes the updated probability distribution of tag number after the tth frame, and $P_{t+1}(n - S)$ denotes the initial probability distribution of tag number at the beginning of the $(t + 1)$th frame. Then the expected tag number in the $(t + 1)$th frame is

$$E_{t+1}(n) = \frac{\sum_{n_{\min}}^{n_{\max}} (n - S) P_{t+1}(n - S)}{\sum_{n_{\min}}^{n_{\max}} P_{t+1}(n - S)}. \tag{17}$$

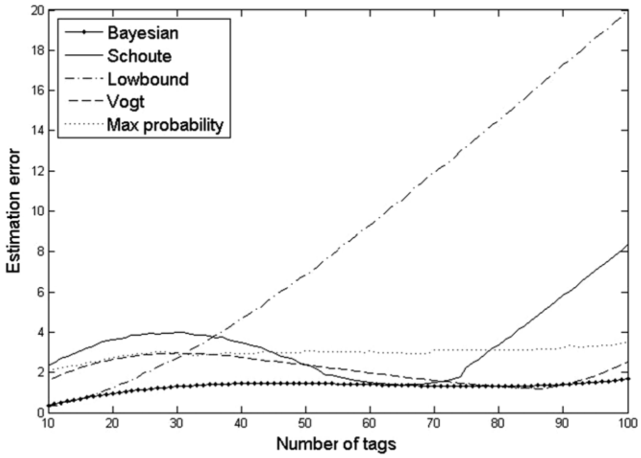

Fig. 2. Error function of tag estimation.

4. Simulation results

Simulations were carried out to investigate the performance of the algorithm proposed in the previous section. The initial frame length was set to 64 slots. Then Monte Carlo method is used in the following steps. A number of tags, ranging from 10 to 100, were put into the frame 1000 times, and then the algorithm was performed to ensure the maximum throughput. Finally, the average results are obtained and several parameters are used to measure the effectiveness of the algorithm. The comparison between different algorithms is made using the error function of tag estimation defined by

$$f(error) = \frac{n - \hat{n}}{n} \cdot 100\%. \tag{18}$$

Fig. 2 presents the error function of five algorithms. Both the lowbound and the Schoute algorithms have relatively larger estimation errors due to the simplicity of these methods. The error of the lowbound algorithm increases linearly to 20% as the tag number increases to 100. The Schoute algorithm produced its minimum error at $n \approx 64$ as expected, since the algorithm estimates the unidentified tags based on the hypothesis that the throughput reaches the peak at the point that $n \approx N$. When the number of the tags is outside the interval [50, 70] the error is about 3 times the proposed algorithm. The error of the Max probability algorithm is no more than 3%. The Vogt algorithm's error is slightly smaller than the error of our algorithm only for a small range of n values around 86 and it is under 2.1% in most of the range, but is much larger than the error of our algorithm when the number of tags is smaller. Clearly, our Bayesian theory based algorithm is more precise in the tag estimation, and consequently produces a stable error that is below 1.6% for all values of n.

Fig. 3 shows the total number of slots used to identify all tags with the initial frame length 64. Again, the Bayesian algorithm shows better performance. When the number of tags is 100, the Schoute algorithm used 10% more slots than the proposed algorithm while the Max probability algorithm used 13% more. The reason that the Vogt algorithm uses more slots for identification is that it has to use a power of 2 as the frame length, while other algorithms use the optimal frame length. The proposed algorithm adjusts the frame length by using the evidence of previous frame, which reduces the error caused by the randomness when the tag selects the slot in the frame.

Let N_{finish} be the total slots for the tags to be entirely identified, then the average throughput of the RFID system is defined by (19):

$$T_{avg} = \frac{n}{N_{finish}}. \tag{19}$$

As can be seen from Fig. 4 when the tag quantity is below 40, the average throughput of the Schoute algorithm is close to our algorithm. But when the tag quantity is greater than 40, the proposed algorithm maintains the average throughput above 35%. When the number of tags is equal to the initial frame length 64, the average throughput of the proposed algorithm reaches 36.8%, the theoretical maximum throughput of the framed slotted ALOHA algorithm.

5. Conclusions

In this paper a dynamic framed slotted ALOHA algorithm based on Bayesian estimation is proposed. It maintains the data collected from previous frames as the experience information of the current frame, while also makes full use of the information that the reader collects in the current frame, and updates and obtains revised information using the Bayesian updating formula. Compared with existing algorithms, this novel algorithm can estimate the number of unidentified tags

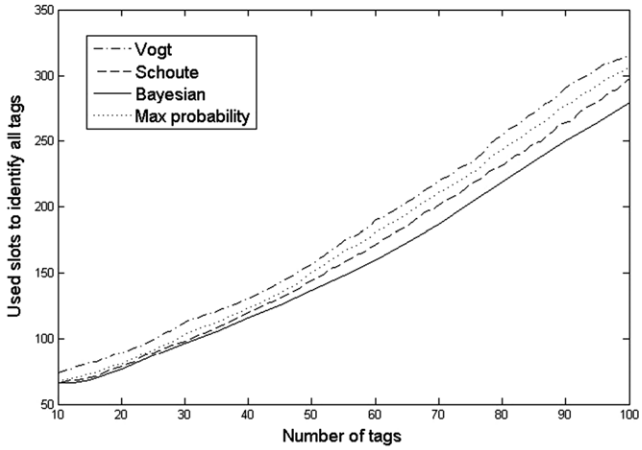

Fig. 3. Used slots to identify all tags.

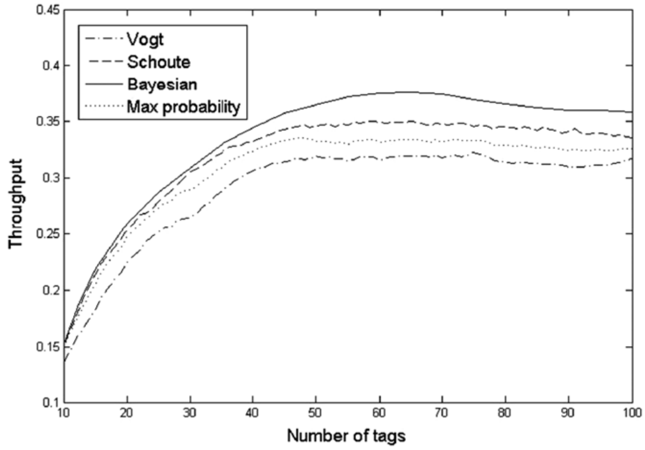

Fig. 4. Average throughput vs number of tags.

more precisely. Our simulation results show that this algorithm can also improve the average throughput of the RFID system, reduce the total slots used to identify tags and increase the tag identification speed.

Acknowledgments

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