Dynamic Framed Slotted ALOHA Algorithms using Fast Tag Estimation Method for RFID System

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Abstract

We propose the ALOHA-based Dynamic Framed Slotted ALOHA algorithm (DFSA) using proposed Tag Estimation Method (TEM) which estimates the number of tags around the reader. We describe the conventional Tag Estimation Method and Dynamic Slot Allocation (DSA), which is the method to dynamically allocate the frame size according to the number of tags. We compare the performance of the proposed DFSA algorithm with the conventional algorithms using simulation. According to the analysis, the proposed DFSA algorithm shows better performance than other conventional algorithms regardless of the number of tags because the proposed algorithm has lower complexity and better delay performance.

1. Introduction

Reliable identification of multiple objects is especially challenging if many objects are present at the same time. Several technologies are available, but they all have limitations. For example, bar code is the most pervasive technology used today, but reading them requires a line of sight between the reader device and the tag, manual, and close-ranging scanning. But Radio Frequency IDentification (RFID) system which is a simple form of ubiquitous sensor networks that are used to identify physical objects permits remote, non-line-of-sight, and automatic reading. Instead of sensing environmental conditions, RFID system identifies the unique tags’ ID or detailed information saved in them attached to objects. Passive RFID system generally consists of a reader and many tags. A reader interrogates tags for their ID or detailed information through an RF communication link, and contains internal storage, processing power, and so on. Tags get processing power through RF communication link from the reader and use this energy to power any on-tag computations. A reader in RFID system broadcasts the request message to the tags. Upon receiving the message, all tags send the response back to the reader. If only one tag responds, the reader receives just one response. But if there is more than one tag response, their responses will collide on the RF communication channel, and thus cannot be received by the reader. The problem is referred to as the “Tag-collision”. An effective system must avoid this collision by using anti-collision algorithm because the ability to identify many tags simultaneously is crucial for many applications[1]-[4]. The anti-collision algorithm using ALOHA-based method described in [5] did not consider the inactivation state in which tags do not respond to next reader’s request temporarily. In Dynamic Slot Allocation (DSA) introduced in [6], there are no detailed methods how to dynamically allocate the frame size. Therefore there is the limitation to apply for those methods in RFID system. In this paper, to improve the performance of conventional ALOHA-based anti-collision algorithms we propose the Dynamic Framed Slotted ALOHA algorithms (DFSA) using Dynamic Slot Allocation (DSA) and Tag Estimation Method (TEM). We compare the performance of DFSA algorithms with that of the conventional Framed Slotted ALOHA (FSA) algorithms using OPNET simulation.

2. Framed Slotted ALOHA algorithm

In this section, we now give the procedure identifying a set of tags, named as the collision arbitration sequence in FSA algorithm, which is for optimizing the relatively low throughput of the ALOHA-based anti-collision algorithm. The purpose of the collision arbitration sequence is to perform a census of the tags present in the reader field and to receive information on tag ID. The collision arbitration sequence uses a mechanism that allocates tag transmissions

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into rounds and slots (time frame). Each slot has duration, long enough for the reader to receive a tag response. This time frame is divided into a number of slots that can be occupied by tags and used for sending their replies. The reader determines the actual duration of a slot. After the reader has sent its request to the tags, it waits for a certain amount of time for their answers. When multiple tags use the same slot, a collision occurs and data get lost. Fig. 1 shows briefly the procedure of FSA algorithm to identify four tags in Table 1. Tags receiving REQ (Request command sent by the reader) randomly select a slot in which to respond. The number of slots in a round referred to as frame size is determined by the reader[5],[7]-[9].

In Fig. 1, TAG1, TAG2, TAG3, and TAG4 selected Slot1, Slot3, Slot3, and Slot4 respectively. Slot2 in which no tags select is an idle slot. Slot1 and Slot4 which TAG1 and TAG4 select respectively will accomplish successful transmission. And the collision will be occurred in Slot3 in which two tags select the same slot, so ID of two collided tags has to be retransmitted in next reader’s request (2nd REQ).

In FSA algorithm, generally, when the number of tags is much higher than the number of slots, the delay to identify a set of tags increases substantially. On the other hand, in a situation that the number of tags is lower than the number of slots, the wasted slots can occur. Therefore, it needs to appropriately vary the frame size according to the number of tags. In next section, we will describe conventional Tag Estimation Method (TEM), which estimates the number of tags around the reader, and Dynamic Slot Allocation (DSA), which dynamically allocates the frame size for the number of tags.

2.1. Tag Estimation Method (TEM)

2.1.1. Methods proposed by Vogt [5] Vogt proposed two methods to estimate the number of tags around the reader. The first estimation method is obtained through the observation that a collision involves at least two different tags. Therefore a lower bound on the value of the estimated number of tags can be obtained by the simple estimation function as

\[
\text{Est}_{\text{Min. bound}} = \text{Number of collided slots} \times 2. \quad (1)
\]

The second method is obtained as follows. Chebyshev’s inequality tells us that the outcome of a random experiment involving a random variable \(X\) is most likely somewhere near the expected value of \(X\). Thus, an alternative estimation function uses the distance between the read results, which are frame size, number of successful slot, number of collided slot, and number of idle slot and the expected value vector to determine the number of tags for which the distance becomes minimal. For more details, refer to [5].

2.1.2. Method using maximum throughput condition
To obtain the number of tags \((C_{\text{tags}})\) related with collision in a slot, we define the collision rate \((C_{\text{rate}})\) as follows.

\[
C_{\text{rate}} = \frac{\text{Prob. that there is the collision in a slot}}{1 - \text{Prob. that a tag transfers successfully}} . \quad (2)
\]

The probability that no tag transmits its ID during a slot is given by

\[
P_{\text{idle}} = (1 - p)^n. \quad (3)
\]

The probability that one tag transmits successfully its ID during a slot

\[
P_{\text{succ}} = np(1 - p)^{n-1}. \quad (4)
\]

Then, the probability that there is the collision in a slot is given by

\[
P_{\text{coll}} = 1 - P_{\text{idle}} - P_{\text{succ}}. \quad (5)
\]

We now define throughput \(S\) as follows.

\[
S = \frac{P_{\text{succ}}}{P_{\text{succ}} + P_{\text{coll}} + P_{\text{idle}}} = np(1 - p)^{n-1}. \quad (6)
\]

The maximum throughput happens when

\[
\frac{dS}{dp} = n(1 - p)^{n-1} - n(n - 1)p(1 - p)^{n-2} = 0. \quad (7)
\]

<table>
<thead>
<tr>
<th>READER</th>
<th>1st REQ</th>
<th>Slot 1</th>
<th>Slot 2</th>
<th>Slot 3</th>
<th>Slot 4</th>
<th>2nd REQ</th>
</tr>
</thead>
<tbody>
<tr>
<td>STATE</td>
<td></td>
<td>1011</td>
<td>IDLE</td>
<td>COLL</td>
<td>0101</td>
<td></td>
</tr>
<tr>
<td>TAG1(1011)</td>
<td>-</td>
<td>1011</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TAG2(1010)</td>
<td>-</td>
<td>1010</td>
<td></td>
<td></td>
<td>1010</td>
<td></td>
</tr>
<tr>
<td>TAG3(0011)</td>
<td>-</td>
<td>0011</td>
<td></td>
<td>0011</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TAG4(0101)</td>
<td>-</td>
<td>0101</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1. used tag ID
From (7) we get
\[ p = \frac{1}{n}. \]  
(8)

A system reaches maximum throughput when \( p \) is equal to \( 1/n \). We get optimal collision rate \( C_{rate} \) for maximum throughput.
\[ C_{rate} = \lim_{n \to \infty} \frac{P_{coll}}{1 - P_{succ}} = 0.4180. \]  
(9)

The number of the collided tags in a slot \( C_{tags} \) is calculated by
\[ C_{tags} = \frac{1}{C_{rate}} = 2.3922. \]  
(10)

Let \( M_{coll} \) be the number of collided slots in a frame after a round. Then, the number of estimated tags is calculated by
\[ \text{Number of estimated tags} = 2.3922 \times M_{coll}. \]  
(11)

2.2. Dynamic Slot Allocation (DSA)

2.2.1. DSA I First of all, we consider the delay \( (D) \) which is the time taken by the tags to transfer their ID successfully and is defined as (12)
\[ D = \text{number of retransmission} \times \text{frame size}. \]  
(12)

Because the value of the frame size is already known after a round, we just need to find the number of retransmission to calculate the delay \( (D) \). The probability \( (p) \) that one tag transmits at the particular slot in a frame is \( 1/L \). Then the probability that one tag successfully transmits its ID during a slot is given by
\[ P_{succ} = \frac{1}{L} \times \left( 1 - \frac{1}{L} \right)^{n-1}. \]  
(13)

And the probability that one tag successfully transmits its ID in a frame \( (L) \) is given by
\[ P_{succ,L} = \frac{1}{L} \times \left( 1 - \frac{1}{L} \right)^{n-1} \times L = \left( 1 - \frac{1}{L} \right)^{n-1}. \]  
(14)

Let \( P_{succ}(k) \) be the probability that one tag transmits its ID successfully in \( k^{th} \) frame. Then \( P_{succ}(k) \) is
\[ P_{succ}(k) = P_{succ,L}(1 - P_{succ,L})^{k-1}. \]  
(15)

Using the mean of geometric distribution, the average number of retransmissions for one tag is
\[ E[X = k] = \sum_{k=1}^{\infty} kP_{succ}(k) = \frac{1}{(1 - \frac{1}{L})^{n-1}}. \]  
(16)

Therefore, we get \( D \) from (12) and (16).
\[ D = \frac{L}{(1 - \frac{1}{L})^{n-1}}. \]  
(17)

It now remains to derive the optimal frame size \( (L_{optimal}) \). To calculate \( L \) when \( D \) is minimum, we differentiate (17) as follows.
\[ \frac{d}{dn} D = \frac{d}{dn} \frac{L}{(1 - \frac{1}{L})^{n-1}} = 0. \]  
(18)

From (18), we get
\[ L_{optimal} = n. \]  
(19)

2.2.2. DSA II The second method to get the optimal frame size is to use the throughput of the system. From (8), the maximum throughput happens when \( p = 1/n \).

Accordingly, we get the optimal frame size \( (L_{optimal}) \) from (19) because the probability \( (p) \) that one tag transmits at the particular slot in a frame is \( 1/L \).
\[ L_{optimal} = n. \]  
(20)

From (19) and (20) we found that the optimal frame size is the same considering the delay or throughput in a system.

Fig. 2 depicts the throughput of the system for the frame size. From Fig. 2, we can get the optimal frame size by determining the same value with the estimated number of tags.
3. Proposed DFSA Algorithm and Performance Analysis

Because of the limitation of conventional Framed Slotted ALOHA algorithm, it needs to estimate number of tags around the reader and dynamically allocate the frame size according to the number of tags. Now, we will describe the DFSA algorithm using proposed TEM.

Given \( L \) slots in a frame and \( n \) tags, the probability that \( r \) out of \( n \) tags transfers their ID in a slot is given by

\[
P(X = r) = \binom{n}{r} \left( \frac{1}{L} \right)^r \left( 1 - \frac{1}{L} \right)^{n-r}.
\]  (21)

The number \( r \) of tags in a particular slot is called the occupancy number of the slots[9]. The expected value of the number of slots with occupancy number \( r \) is given by

\[
E(X = r) = L \binom{n}{r} \left( \frac{1}{L} \right)^r \left( 1 - \frac{1}{L} \right)^{n-r}.
\]  (22)

To estimate the number \( n \) of tags, we define the collision ratio \( (C_{\text{ratio}}) \), which means the ratio of the number of the slots with collision to the frame size, is given by

\[
C_{\text{ratio}} = 1 - \left( 1 - \frac{1}{L} \right)^n \left( 1 + \frac{n}{L-1} \right).
\]  (23)

After a round, we know the frame size and the collision ratio. Based on this information, we can estimate the number of tags. So, the frame size is equal to the number of tags estimated before

\[
800 \text{ us } \quad 200 \text{ us } \quad \text{Tag Identification Process}
\]

Fig. 3 shows the collision ratio for the number of tags. In Fig. 3, if the frame size is 320 and the collision ratio is 0.46323 measured by the reader, the number of estimated tags is 400.

4. Simulation results

Fig. 4 shows the frame structure used for obtaining the tag identification time[6]. The algorithm is operated by the reader-driven method. It is assumed that the length of tag ID is 36 bits and there are no errors in wireless channel during the algorithm procedure.

Fig. 5 represents the number of round versus the number of tag for the different algorithm. If we use the FSA algorithm in RFID system, the round size will increase sharply after certain number of tags. So as increasing the overhead such as bits for power-up, synchronization, and error check, the performance of FSA will decrease. But other algorithms estimating the number of tags show comparatively the stable performance.

Fig. 6 depicts the tag identification time for the number of tags. In Fig. 6, SLOT 128 and SLOT 256 mean conventional FSA algorithms using the fixed frame size with 128 slots and 256 slots respectively. 2.3922 means the algorithm using maximum throughput condition, Vogt 1 and Vogt 2 represents the algorithms proposed by Vogt.

And DFSA represents the proposed Dynamic Framed Slotted ALOHA algorithm using proposed TEM and conventional DSA. The performance of conventional FSA using the fixed frame size algorithm varies according to the number of tags. In Fig 6, when the number of tags is in the range of 0 to 300 and the frame size is 128 (SLOT 128), FSA algorithm shows better performance. While the number of tag is more than 300, the identification time of SLOT 128 increases substantially according to the increase of the number of tags. Therefore, if FSA algorithm is used for the purpose of resolving anti-collision problem in RFID system, it may show the unstable performance as the number of tags increases. However, the algorithms using TEM show relatively the stable performance regardless of the number of tags. From Fig.6, out of algorithms estimating the number of tags, the proposed DFSA algorithms show better perfor-
mance than conventional FSA algorithms and other algorithms using TEM regardless of the number of tags because it has lower complexity and better delay performance.

5. Conclusion

We proposed the Dynamic Framed Slotted ALOHA algorithm (DFSA) using proposed Tag Estimation Method (TEM) which estimates the number of tags around the reader using collision ratio that means the ratio of the number of the slots with collision to the frame size. We described the conventional Tag estimation Method and Dynamic Slot Allocation (DSA), which is the method to dynamically allocate the frame size according the number of tags. We also compared the performance of the proposed DFSA algorithm with the conventional Framed Slotted ALOHA algorithm (FSA), two algorithms proposed by Vogt, and the algorithm which uses maximum throughput condition. Out of those algorithms estimating the number of tags, the proposed DFSA algorithm shows better performance than conventional FSA algorithms and other algorithm using TEM regardless of the number of tags. Consequently, if the proposed DFSA algorithm is used in RFID system where the ability to simultaneously identify many tags is crucial for many applications, it will contribute to improve the performance of RFID system because the reader can identify more tags with shorter time.

References