Accurate Tag Estimation for Dynamic Framed-Slotted ALOHA in RFID Systems

Jun-Bong Eom and Tae-Jin Lee, *Member, IEEE*

***Abstract*—Dynamic Framed-Slotted ALOHA (DFSA) is one of the most popular algorithms to resolve tag collision in RFID systems. In DFSA, it is widely known that the optimal performance is achieved when the frame size is equal to the number of tags. So, a reader dynamically adjusts the next frame size according to the current number of tags. Thus it is important to estimate the number of tags accurately. In this paper, we propose a novel tag estimation method for DFSA. We compare the performance of the proposed method with those of other existing methods. And, simulation results show that our scheme improves the accuracy of tag estimation and the speed of tag identification.**

***Index Terms*—Anti-collision, DFSA, frame size, RFID, tag estimation, tag identification.**

I. Introduction

When more than one tag respond simultaneously to a reader's request in Radio Frequency IDentification (RFID) systems, tag collision occurs. To resolve the tag collision problem, many RFID tag anti-collision algorithms have been presented. They are classified into tree-based algorithms [2] and ALOHA-based algorithms [1]. Among tree-based algorithms, the binary tree algorithm is one of the most representative algorithms. If a collision occurs, it tries to resolve the collision by splitting the colliding tags into two subsets, i.e., the tags in a collided time slot randomly choose one slot out of the next two time slots and retransmit. The process is repeated until no collision occurs and all tags are identified. However, when the number of tags is large, it may experience consecutive collisions since the colliding tags are successively grouped into two subsets, and each subset may still contain many tags resulting in collisions.

ALOHA-based protocols mainly use Framed-Slotted ALOHA (FSA). In FSA, each unread tag randomly selects one of the time slots of a frame. Unless the tag successfully transmits its information to a reader, it will try again in the next frame. The performance of FSA depends on the number of tags and the frame size, and its optimal success probability is known as $1/e$ when the frame size equals to the number of tags [4]. So, for high performance, an appropriate frame size should be decided according to the varying number of tags to be identified, and the mechanism is referred to as Dynamic Framed-Slotted ALOHA (DFSA). In DFSA, in order to decide the next optimal frame size, the number of unread tags, which is called the backlog, has to be estimated with care at each frame.

The Schoute tag estimation mechanism in [4] is based on the number of collisions in a frame. The number of tags is estimated by multiplying the number of collision slots in a frame by the expected number of tags per collision slots (=2.39), which is the same for all frames regardless of various number of tags and frame size. In the mechanisms by Vogt [5], Chen *et al*. [6], and Cha *et al*. [7], estimation of the number of tags is based on the success, collision, and idle probability in a frame. They require rather large computational load, or they are sensitive to the probabilities. In this paper, we propose an accurate and simple tag estimation method for DFSA in RFID systems. The proposed scheme determines the next frame size by multiplying a frame-specific optimal constant value to the number of collision slots in a frame.

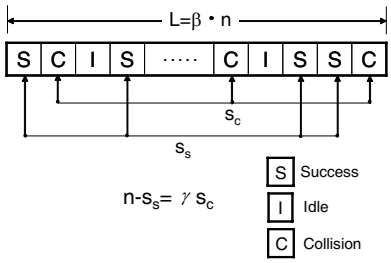

Fig. 1. The relation between the frame size L and the backlog ($=n - s_s$).

II. The Proposed Tag Estimation Mechanism

We assume that the frame size L is the estimated number of tags n multiplied by a proportional factor β, which needs to be determined.

$$L = \beta \cdot n. \tag{1}$$

When a collision occurs, we assume that the expected number of tags transmitted in the collided time slot is γ. Then, the backlog (next frame size) is found as follows (see Fig. 1).

$$backlog = n - s_s = \gamma \cdot s_c, \tag{2}$$

where s_s and s_c are the number of success slots and the number of collision slots in the frame, respectively. Our proposed tag estimation mechanism estimates the number of tags to be identified, i.e., backlog, from s_s, s_c, L, and γ or

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J.-B. Eom was with the School of Information and Communication Engr., Sungkyunkwan University, Suwon 440-746, Korea, and is now with Digital Media & Communications, Samsung Electronics, Suwon 442-742, Korea.

T.-J. Lee is with the School of Information and Communication Engr., Sungkyunkwan University, Suwon 440-746, Korea (e-mail: tjlee@ece.skku.ac.kr).

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β. Now we present a mechanism to find γ or β in a simple iterative way.

The probability that r tags among n tags occupy a slot can be approximated by a binomial distribution [3]

$$P_r = \binom{n}{r}\left(\frac{1}{L}\right)^r\left(1-\frac{1}{L}\right)^{n-r}. \quad (3)$$

If the frame size L is sufficiently large, Eq. (3) can be approximated by a Poisson distribution with mean n/L. When $r=0$ in Eq. (3), the probability that no tags occupy a slot

$$P_0 = \left(1-\frac{1}{L}\right)^n \approx e^{-\frac{n}{L}}. \quad (4)$$

When $r=1$ in Eq. (3), the probability that only one tag occupies a slot

$$P_1 = n\frac{1}{L}\left(1-\frac{1}{L}\right)^{n-1} \approx n\frac{1}{L}\left(\frac{L}{L-1}\right)e^{-\frac{n}{L}}. \quad (5)$$

Then, the left hand side of Eq. (2) is approximated by

$$\begin{aligned} n-s_s &= n - L\cdot n\frac{1}{L}\left(1-\frac{1}{L}\right)^{n-1} \\ &\approx n\left(1-\left(\frac{L}{L-1}\right)e^{-\frac{n}{L}}\right) \\ &\approx n\left(1-e^{-\frac{n}{L}}\right) = n\left(1-e^{-\frac{1}{\beta}}\right), \end{aligned} \quad (6)$$

where $\beta = \frac{L}{n}$ from Eq. (1). The right hand side of Eq. (2) is

$$\begin{aligned} \gamma\cdot s_c &= \gamma\cdot L\left(1-\left(1-\frac{1}{L}\right)^n - n\frac{1}{L}\left(1-\frac{1}{L}\right)^{n-1}\right) \\ &\approx \gamma\cdot L\left(1-e^{-\frac{n}{L}} - n\frac{1}{L}\left(\frac{L}{L-1}\right)e^{-\frac{n}{L}}\right) \\ &\approx \gamma\cdot\beta n\left(1-\left(1+\frac{1}{\beta}\right)e^{-\frac{1}{\beta}}\right). \end{aligned} \quad (7)$$

Solving Eqs. (2), (6), and (7) for γ, we can obtain

$$\gamma = \frac{1-e^{-\frac{1}{\beta}}}{\beta\left(1-\left(1+\frac{1}{\beta}\right)e^{-\frac{1}{\beta}}\right)}. \quad (8)$$

When s_c and s_s are measured in the frame of size L, β can be calculated by solving the following equation from Eqs. (1), (2) and (8).

$$L = \beta\cdot n = \beta\cdot(\gamma\cdot s_c + s_s). \quad (9)$$

And, the backlog is estimated as

$$backlog = \gamma\cdot s_c = \frac{1-e^{-\frac{1}{\beta}}}{\beta\left(1-\left(1+\frac{1}{\beta}\right)e^{-\frac{1}{\beta}}\right)}\cdot s_c. \quad (10)$$

However, it is challenging to find a closed form solution for β and γ in Eq. (8). So, we propose an iterative algorithm to find β and γ.

Let β_k and γ_k be the kth iterative value of β and γ, respectively. First, we let $x=\frac{1}{\beta_1}$ and assume that $\beta_1\to\infty(x\to 0)$. Then, γ_1 is obtained from Eq. (8) by the L'hôpital's rule.

$$\gamma_1 = \lim_{\beta_1\to\infty}\frac{1-e^{-\frac{1}{\beta_1}}}{\beta_1\left(1-\left(1+\frac{1}{\beta_1}\right)e^{-\frac{1}{\beta_1}}\right)} = 2. \quad (11)$$

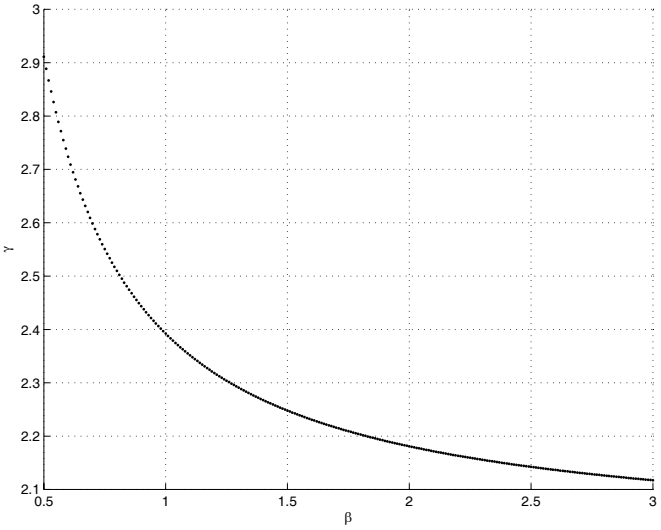

Fig. 2. Relationship between β and γ in Eq. (8).

By Eqs. (1) and (2), β_2 can be inferred from γ_1.

$$\beta_2 = \frac{L}{\gamma_1\cdot s_c + s_s} < \beta_1, \quad (12)$$

since L, s_c, s_s and γ_1 are finite constant values. We can then acquire γ_2 from β_2,

$$\gamma_2 = \frac{1-e^{-\frac{1}{\beta_2}}}{\beta_2\left(1-\left(1+\frac{1}{\beta_2}\right)e^{-\frac{1}{\beta_2}}\right)}. \quad (13)$$

Fig. 2, which depicts Eq. (8), shows that γ is inversely proportional to β. So $\gamma_2>\gamma_1$ because $\beta_2<\beta_1$, and $\beta_3<\beta_2$ because $\gamma_2>\gamma_1$. Thus, we have the iterative algorithm

$$\begin{aligned} \beta_k &= \frac{L}{\gamma_{k-1}\cdot s_c + s_s}, \\ \gamma_k &= \frac{1-e^{-\frac{1}{\beta_k}}}{\beta_k\left(1-\left(1+\frac{1}{\beta_k}\right)e^{-\frac{1}{\beta_k}}\right)}. \end{aligned} \quad (14)$$

Then the sequence $\{\beta_k\}$ satisfies

$$\beta_k < \beta_{k-1} < \cdots < \beta_2 < \beta_1. \quad (15)$$

Since the sequence $\{\beta_k\}$ is monotonically decreasing and bounded, the sequence has a finite limit. Hence, the sequence $\{\beta_k\}$ converges to a limit. One can use the iterative algorithm Eq. (14) starting from $\beta_1=\infty, \gamma_1=2$, and find the limit value γ_{k^*} at the k^*th iteration, at which the following condition is met for a threshold $\epsilon_{threshold}$ [1]

$$|\gamma_{k^*-1}-\gamma_{k^*}| < \epsilon_{threshold}. \quad (16)$$

Then the backlog (desirable next frame size) can be found as

$$backlog^* = \gamma_{k^*}\cdot s_c. \quad (17)$$

[1]The sequence in Eq. (14) tends to converge fast for a reasonable threshold $\epsilon_{threshold}$.

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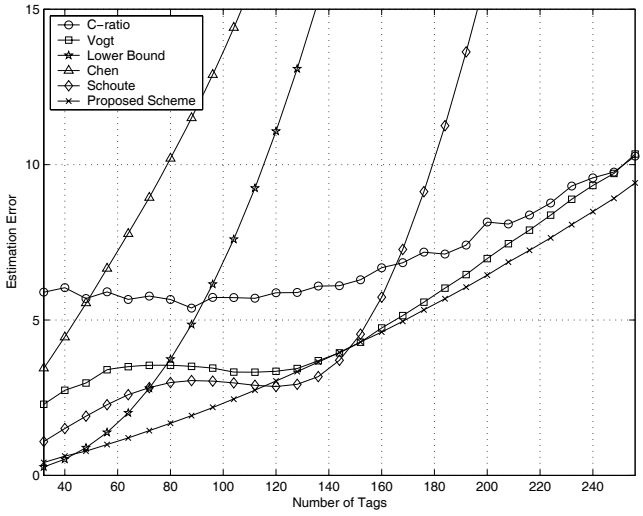

Fig. 3. Difference between the real number and the estimated number of tags when the frame size is set to 128.

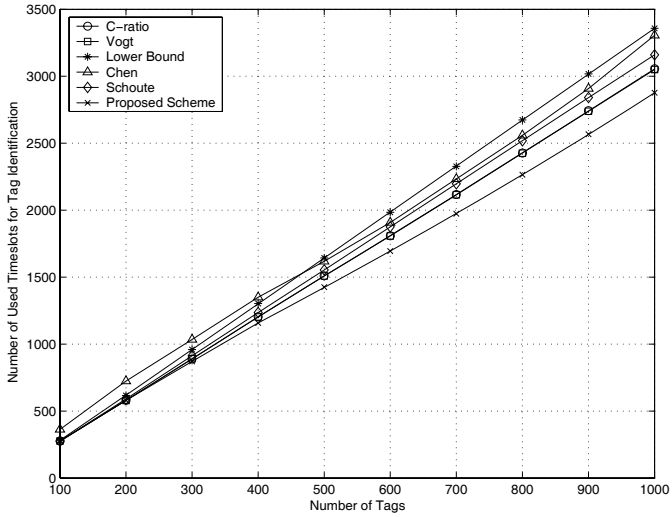

Fig. 4. The number of used time slots for tag identification when the frame size is set to the estimated backlog value.

III. Simulation Results

We consider a single reader and tags under error-free channel environment. To evaluate performance, we compare the estimation accuracy of the proposed scheme with those of other schemes, and we measure the number of time slots used to read out all tags when each estimation method is applied for DFSA. In the proposed method, $\epsilon_{threshold}$ is set to 0.001. C-ratio corresponds to the mechanism in [7].

Fig. 3 shows the mean estimation error which is defined as the mean difference between the real number and the estimated number of unread tags (backlog). For the simulation, we set the frame size to 128 and vary the number of tags from 32 to 256. When the number of tags is nearly equal to the frame size, the Schoute method is the most efficient among the methods. However, the estimation errors of the Lower Bound method ($backlog = 2 \cdot s_c$) and the Schoute method may increase. Among the existing methods, the Vogt method shows reasonable performance. However, to find the minimum value of the vector distance, lots of computational load is required. Fig. 3 also presents that the proposed method provides more precise estimation than the Vogt method. And we can see the accuracy of the proposed method is superior to that of other methods except the region in which the number of tags is similar to the frame size.

In Fig. 4, we compare the number of used time slots for tag identification when the frame size is set to the estimated backlog value. An initial frame size is set to 64, and the number of tags varies from 100 to 1000. Fig. 4 shows that when the number of tags is 1000, the proposed method requires 14.3%, 9.0% and 5.7% less time slots than the Lower Bound, the Schoute and the Vogt (or C-ratio) method, respectively. [2] It demonstrates the performance of DFSA can be improved by using the proposed accurate tag estimation mechanism.

[2]The proposed method demonstrates similar performance gain under error-prone channel. In terms of complexity, our mechanism is less complex than the Vogt method, which requires searching for a vector space, or as simple as the others.

IV. Conclusion

In this paper, to achieve the optimal performance of DFSA in RFID systems, we have proposed an efficient tag estimation method. The proposed method estimates the number of unread tags by multiplying the number of collided time slots by a well-defined factor, which is found by analysis based on the number of successful and collided time slots. When the number of tags is not given, which is usual in practice, it can achieve accurate estimation performance. The simulation results show that our scheme indeed improves the accuracy of tag estimation and consumes less time slots than others.

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