A Scheme for Estimating Number of Tags in FSA-based RFID Systems

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Abstract—An RFID system consists of radio frequency tags attached to objects that need to be identified and one or more electromagnetic readers. Unlike the traditional bar code system, the great benefit of RFID technology is that it allows information to be read without requiring contact between the tag and the reader. For this contact-less feature, RFID technology in the near future will become an attractive alternative to bar code in many application fields. In almost all the 13.56MHz RFID systems, FSA (Framed Slot ALOHA) algorithm is used for identifying multiple tags in the reader's identification range. In FSA algorithm, the tag identification time and system efficiency depend mainly on the number of tags and frame size. In this paper, we propose a tag number estimation scheme and a dynamic frame size allocation scheme based on the estimated number of tags.

Index Terms—RFID, Tag number estimation, Anti-collision algorithm, FSA

I. INTRODUCTION

RFID system has been expected to be widely adapted in a variety of application fields such as public transportation, production control, animal identification, and object tracking [1]. In general, an RFID system consists of radio frequency tags attached to objects that need to be identified and one or more electromagnetic readers. Unlike the traditional bar code system, the great benefit of RFID technology is that it allows information to be stored and read without requiring either contact or line of sight between the tag and the reader. For this contact-less feature, RFID technology in the near future will become ubiquitous and an attractive alternative to bar code in many application fields [2][3].

The reader in RFID system broadcasts a request message to tags asking for the tag identification codes in order to identify multiple tags in its identification range. Upon receiving this message, all tags in the reader's identification range send their response back to the reader at the same time. If only one tag answers, the reader receives just one message which is correctly decoded. If two or more tags answer, their messages will collide on the RF communication channel and cannot be correctly received by the reader. This may lead to mutual interference, which is referred to as a collision [4]. A technical scheme that handles multiple-access without any interference is called as an anti-collision algorithm [5][6].

There are two types of anti-collision algorithms: deterministic and probabilistic algorithm [1][4]. The deterministic algorithm resolves collisions by muting subsets of tags that are involved in a collision. By successively muting larger subsets, only one tag will be left and finally led to successful transmission. Binary tree and query tree algorithms are the two main methods of the deterministic algorithm. The probabilistic algorithm is based on an ALOHA-like protocol that provides slots for the tags to send their data. Whenever a collision has occurred, another frame of slots is provided, and the tags that are involved in collisions will choose different slots in the next read cycle.

In almost all the 13.56 MHz RFID systems, FSA algorithm is used for anti-collision algorithm [7]. The FSA algorithm is based on the slotted ALOHA scheme with a fixed frame size. The performance of FSA algorithm is dependent on the frame size and the number of tags in the reader's identification range. Therefore, we propose a tag number estimation and dynamic frame size allocation scheme. In the proposed scheme, the reader estimates the number of tags in its identification range at every read cycle, and dynamically allocates the frame size depending on the estimated number of tags.

This paper is organized as follows. In Section II, we analyze the performance of the traditional FSA algorithm. A dynamic frame size allocation scheme is proposed in Section III, and Section IV presents the

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tag number estimation scheme. In Section V, we show the simulation results. In Section VI, conclusion and future work complete the paper.

II. ANALYSIS OF FSA

For analyzing the performance of FSA algorithm, it is assumed that a frame consists of N slots and there are n tags in the reader's identification range. Also, we assume that the tag selects one of N slots with the equal probability. For a given time slot, the number of tags allocated into the slot is a binomial distribution with n Bernoulli experiments and $1/N$ occupied probability. Therefore, the probability $B_{n,N}(r)$ that r tags out of n respond in a given slot defined as follows [7]:

$$B_{n,N}(r) = \binom{n}{r}\left(\frac{1}{N}\right)^r\left(1-\frac{1}{N}\right)^{n-r} \quad (1)$$

Because a frame consists of N slots, the expected number of slots $a_{n,N}(r)$ that r tags respond is given by

$$\begin{aligned} a_{n,N}(r) &= N \cdot B_{n,N}(r) \\ &= N\binom{n}{r}\left(\frac{1}{N}\right)^r\left(1-\frac{1}{N}\right)^{n-r} \end{aligned} \quad (2)$$

Similarly, the expected number of slots $a_{n,N}(0)$ that no tag answers, $a_{n,N}(1)$ that only one tag answers, and $a_{n,N}(\geq 2)$ that two or more tags answer are defined as follows, respectively.

$$\begin{aligned} a_{n,N}(0) &= N \cdot B_{n,N}(0) \\ &= N\left(1-\frac{1}{N}\right)^{n} \end{aligned} \quad (3)$$

$$\begin{aligned} a_{n,N}(1) &= N \cdot B_{n,N}(1) \\ &= n\left(1-\frac{1}{N}\right)^{n-1} \end{aligned} \quad (4)$$

$$\begin{aligned} a_{n,N}(\geq 2) &= \sum_{r=2}^{n} a_{n,N}(r) \\ &= \sum_{r=2}^{n} N\binom{n}{r}\left(\frac{1}{N}\right)^r\left(1-\frac{1}{N}\right)^{n-r} \end{aligned} \quad (5)$$

In the above equations, $a_{n,N}(0)$ and $a_{n,N}(1)$ mean the average number of empty slots and successful slots, respectively. And $a_{n,N}(\geq 2)$ means the average number of collision slots.

If the system efficiency E is defined as the average number of singly occupied slots in a frame, it is given by

$$E = \frac{n}{N}\left(1-\frac{1}{N}\right)^{n-1} \quad (6)$$

If we define the tag identification delay as the delay until all the tags are completely identified, it can be represented with the product of the number of retransmissions due to the collision and the frame size. Let $S_{n,N}$ denote the probability that a tag is successfully identified within a frame and $F_{n,N}$ the probability that a tag is not identified within a frame. These two probabilities are given as follows, respectively.

$$\begin{aligned} S_{n,N} &= \frac{B_{n,N}(1)}{n} \cdot N \\ &= \left(1-\frac{1}{N}\right)^{n-1} \end{aligned} \quad (7)$$

$$\begin{aligned} F_{n,N} &= 1 - S_{n,N} \\ &= 1-\left(1-\frac{1}{N}\right)^{n-1} \end{aligned} \quad (8)$$

Let $S_{n,N}(k)$ be the probability that a tag is successfully identified at the k-th frame. It can be defined as the probability that (k-1) consecutive collisions occur and the identification is done at the k-th frame. The probability $S_{n,N}(k)$ and the average number of retransmissions $E[S_{n,N}(k)]$ can be given by

$$S_{n,N}(k) = F_{n,N}^{k-1} \cdot \left(1-F_{n,N}\right) \quad (9)$$

$$\begin{aligned} E[S_{n,N}(k)] &= \left(1-F_{n,N}\right)\sum_{k=1}^{\infty} k \cdot F_{n,N}^{k-1} \\ &= \frac{1}{\left(1-\frac{1}{N}\right)^{n-1}} \end{aligned} \quad (10)$$

We defined the tag identification delay D as the product of the number of retransmissions given in Eq.(10) and the frame size N. Therefore, the tag identification delay D is given by

$$\begin{aligned} D &= E[S_{n,N}(k)] \cdot N \\ &= \frac{N}{\left(1-\frac{1}{N}\right)^{n-1}} \end{aligned} \quad (11)$$

Fig. 1 and Fig. 2 show the system efficiency and identification delay as a function of the number of tags, respectively. As depicted in the figures, if the frame size is small, the system efficiency decreases and the identification delay increases rapidly as the number of tags increases due to a lot of collisions. On the other hand, if the number of tags is small and the frame size is large, a lot of time slots will be wasted. So, the system efficiency decreases and the identification delay increases compared with the small frame size as the number of tags decreases.

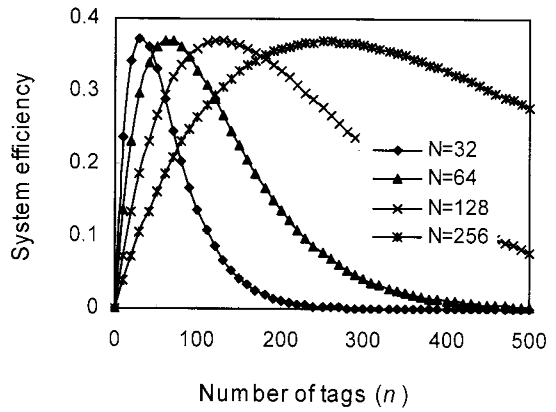

Fig. 1. System efficiency for FSA algorithm.

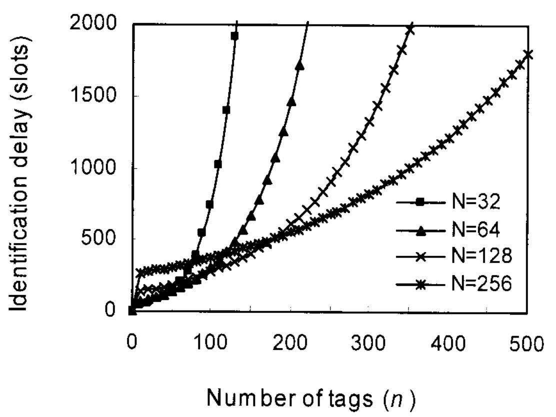

Fig. 2. Identification delay for FSA algorithm.

As shown in the figures, the performances of FSA algorithm in RFID system are dependent on the frame size and the number of tags in the reader's identification range. Therefore, for achieving the maximum performances, it is necessary to allocate the frame size dynamically based on the number of tags in the reader's identification range.

III. DYNAMIC FRAME SIZE ALLOCATION

In this section, we propose a dynamic frame size allocation scheme for obtaining the maximum system efficiency and the minimum tag identification delay. In the proposed scheme, the frame size is dynamically allocated at every read cycle based on the number of tags within the reader's identification range.

At first, the frame size for the maximum system efficiency is considered. In order to maximize the system efficiency, we take the first derivative of system efficiency E given in Eq.(6) with respect to the frame size N. The first derivative of system efficiency is given as follows.

$$\frac{dE}{dN} = \frac{n(n-N)(N-1)^{n-2}}{N^{n+1}} \quad (12)$$

The optimal frame size for maximizing the system efficiency can be taken when we let Eq.(12) equal to zero. Therefore, the maximum system efficiency occurs at $N=n$ or $N=1$. Generally, because the frame size is greater than 1 in order for the reader to identify multiple tags, the maximum system efficiency can be achieved at $N=n$. Hence, the optimal frame size is equal to the number of tags within the reader's identification range.

Fig. 3 depicts the system efficiency for the frame size according to the different number of tags. As depicted in the figure, the maximum system efficiency can be obtained when the frame size is equal to the number of tags.

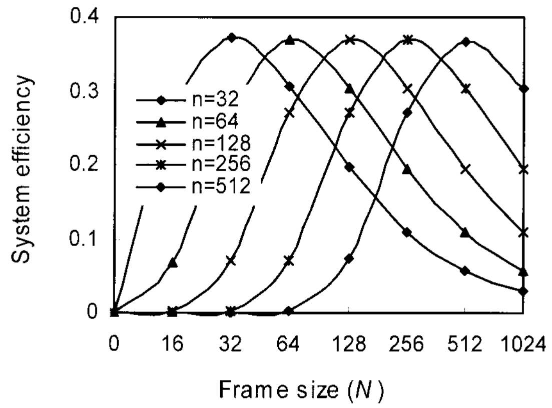

Fig. 3. System efficiency according to frame size.

Secondly, the frame size for the minimum identification delay is considered. In order to minimize the identification delay, we take the first derivative of Identification delay D given in Eq.(11) with respect to the frame size N. The optimal frame size for minimizing the tag identification delay can be taken when we let the first derivative equal to zero. The first derivative of identification delay is given as follows.

$$\frac{dD}{dN} = \frac{N^{n-2}(N-n)}{(N-1)^{n-1}} \quad (13)$$

Therefore, the minimum identification delay occurs at $N=n$ or $N=0$. In general, because the reader should allocate the frame size for identifying the tags, the minimal identification delay can be achieved at $N=n$. Hence, the optimal frame size is equal to the number of tags within the reader's identification range.

Fig. 4 shows the identification delay for the frame size according to the different number of tags. As shown in the figure, the minimum identification delay can be taken when the frame size is equal to the number of tags.

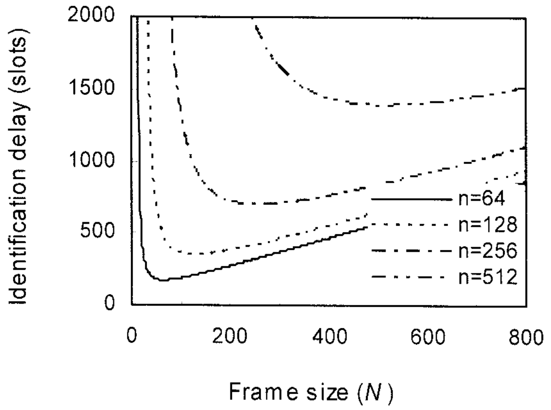

Fig. 4. Identification delay according to frame size.

From Fig. 3 and Fig. 4, we can figure out that the optimal frame size for maintaining the maximum system efficiency and the minimum identification delay is equal to the number of tags. Therefore, in the proposed algorithm, the reader allocates the frame size equal to the number of tags in its identification range at every read cycle.

IV. TAG NUMBER ESTIMATION

In the proposed tag number estimation scheme, the reader estimates the number of tags by combining the information obtained after a read cycle with the result of probabilistic analysis. Let N_e and N_s be the number of empty slots and successful slots observed after the read cycle, respectively. If we assume that the number of empty slots and successful slots observed after the read cycle is equal to their expected values in Eq.(3) and (4), respectively, then N_e and N_s can be given as follows.

$$N_e = N\left(1-\frac{1}{N}\right)^n \quad (14)$$

$$N_s = n\left(1-\frac{1}{N}\right)^{n-1} \quad (15)$$

By solving Eq.(14) and (15) for the number of tags n, we obtain

$$n = (N-1)\frac{N_s}{N_e} \quad (16)$$

The number of tags that will be involved in the next read cycle is equal to the number of colliding tags n_c. Therefore, the number of colliding tags can be estimated by subtracting Ns from Eq.(16) as follows.

$$n_c = (N - N_e - 1)\frac{N_s}{N_e} \quad (17)$$

Because the reader can obtain the number of successful slots and empty slots after the read cycle, it also can estimate the number of unread tags from Eq.(17). However, as shown in Eq.(17), if here are neither successful slots nor empty slots, we cannot use the above equation. Therefore, the proposed scheme supplements the result of probabilistic analysis for the exact estimation.

If we let α be the average number of tags in each collision slot, α can be given by

$$\alpha = \frac{\sum_{r=2}^{n} rN\binom{n}{r}\left(\frac{1}{N}\right)^r\left(1-\frac{1}{N}\right)^{n-r}}{N - N\left(1-\frac{1}{N}\right)^n - n\left(1-\frac{1}{N}\right)^{n-1}} \quad (18)$$

Fig. 5 shows the average number of tags in a collision slot when the frame size is equal to the number of tags. In Section III, we already derived that the optimal performance for the system efficiency and identification delay can be obtained when the frame size is equal to the number of tags. Therefore, as shown in the figure, the average number of tags in each collision slot is 2.4. If we let N_c be the number of collision slots, the number of unread tags are give by

$$n_c = 2.4N_c \quad (19)$$

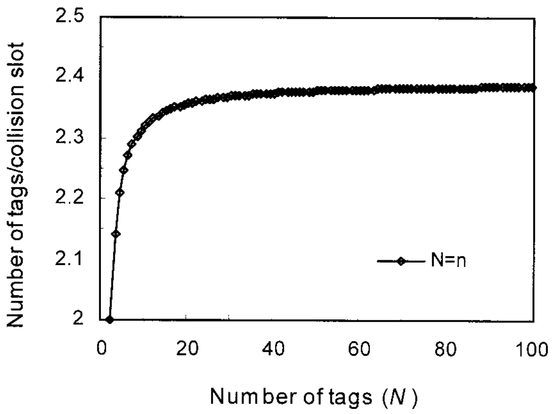

Fig. 5. Number of collision tags per collision slot.

By combining the observed result in Eq.(17) with the probabilistic result in Eq.(19), we can estimate the number of unread tags as following.

$$n_c = \begin{cases} (N - N_e - 1)\dfrac{N_s}{N_e} & \text{, if } N_e \neq N_s \neq 0 \\ 2.4N_c & \text{, otherwise} \end{cases} \quad (20)$$

V. SIMULATION RESULTS

In this paper, the computer simulations are performed to compare the performance of proposed algorithm with the optimal algorithm with respect to the system efficiency and identification delay. It is assumed that the frame structure and sot length for simulations are same with the 13.56MHz RFID system proposed by Auto-ID center [8]. Fig. 6 and Table 1 show the frame structure and read cycle timing of 13.56MHz RFID system for obtaining the tag identification delay, respectively. The EPC code length assumes to be 64 bits for the values in the Table 1.

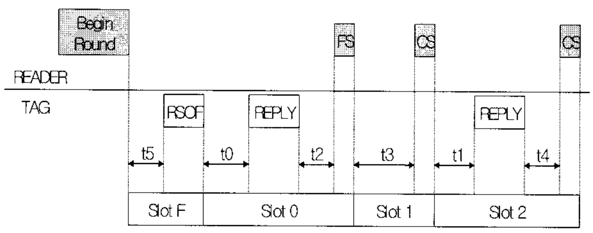

Fig. 6. Frame structure.

Table 1. Read cycle timing.

Items		Value (μsec)
Begin Round		1.623.68
Slot F		188.79
Slot 0	Success	2,756.48
	Collision	2,114.56
	Empty	226.54
Slot i (i≠0)	Success	2,945.27
	Collision	2,303.35
	Empty	490.85

The system efficiency and identification delay for the proposed algorithm are illustrated in Fig. 7 and 8 compared with the optimal algorithm. The optimal algorithm presented in the figures assumes that the reader exactly knows the number of tags within its identification range before the read cycle. As shown in Fig. 5, the system efficiency of optimal algorithm is about 0.36, while that of proposed algorithm is about 0.33. Also, as shown in Fig. 8, there are no significant differences of identification delay between the optimal and proposed algorithm.

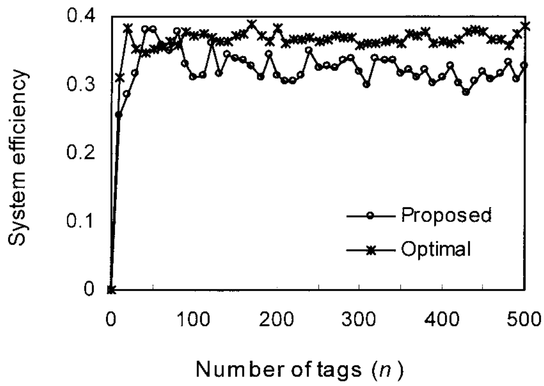

Fig. 7. System efficiency vs. number of tags.

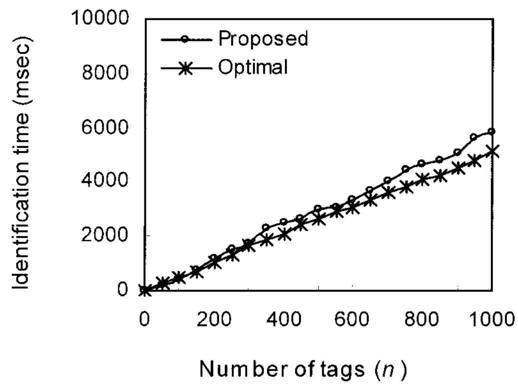

Fig. 8. Identification delay vs. number of tags.

VI. CONCLUSIONS

This paper proposed the scheme that the reader estimates the number of tags within its identification range and allocates dynamically the frame size based on the estimated number of tags. The proposed estimation scheme used the information observed after a read cycle and the result of probabilistic analysis. With the computer simulations, the performances of proposed scheme are compared with the optimal scheme, which is assumed that the reader exactly knows the number of tags before the read cycle. The simulation results showed that there were no significant differences between the proposed and optimal scheme with respect to the system efficiency and identification delay.

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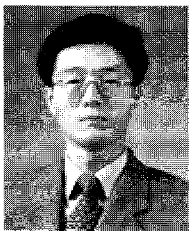

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