An Accurate Tag Estimate Method for Improving the Performance of an RFID Anticollision Algorithm Based on Dynamic Frame Length ALOHA

Wen-Tzu Chen

***Abstract*—In a radio-frequency identification (RFID) system, the dynamic frame length ALOHA protocol is widely adopted to solve the anticollision problem. Analysis for the anticollision problem can be divided into two primary parts. The concern of the first part is how to precisely estimate the number of tags. The other part involves determination of dynamic frame length to achieve maximum throughput or channel usage efficiency. In this paper, we present an accurate method for estimating tag quantity. This method is based on the maximum *a posteriori* probability decision. We also derive the optimal frame length using radio channel efficiency. Simulation results indicate the tag estimate error of the proposed method is less than 4%. Use of our proposed tag estimate method together with optimal frame length can achieve close to the theoretical maximum throughput of the framed ALOHA algorithm.**

***Note to Practitioners*—A tag estimate method presented here is capable of precisely estimating the number of tags in resolving multiple-tag access using dynamic frame length ALOHA. The optimal frame length for obtaining the maximum radio channel efficiency is derived. Performance measures including tag estimate error and total read time show that our proposed anticollision algorithm is superior in comparison to previously published work. Since the frame length update mechanism including tag estimate method and the setting of frame length is not specified in current RFID standards such as ISO 18000–6 and ISO 14443–3, our proposed anticollision algorithm can be useful for engineers to implement the dynamic frame length ALOHA algorithm in a real RFID system. Also, using our method can achieve uplink throughput close to the theoretical maximum value 0.368 of the framed ALOHA algorithm.**

***Index Terms*—Anticollision, framed ALOHA, radio-frequency identification (RFID), tag estimate.**

I. Introduction

IN RECENT YEARS, radio-frequency identification (RFID) technology has become a viable alternative for identifying objects automatically. It bridges gaps in information technology systems previously bridged by manual data entry. There are many promising RFID applications. For example, RFID functions are being used in passports issued by many countries, including the United States, the United Kingdom, and Malaysia. In the near future, RFID technology will become ubiquitous when the cost of tags reduces to an acceptable level.

In an RFID system, when numerous tags are present at the same time in the interrogation zone of a single reader, the system requires an anticollision algorithm to read tags' ID or data from individual tags. In [1], the author provided the foundation for applying anticollision algorithms to RFID systems and described the mechanism of how the protocol overcomes collisions. The primary concern in an anticollision scheme is how to read multiple tags as fast and reliably as possible [2]. RFID anticollision protocols can be categorized into tree-based and ALOHA-based ones [3]. Tree-based algorithms resolve collisions by muting subsets of tags that are involved in a collision. Successively muting larger subsets finally leads to successful transmission of a tag's identification. The tree-based algorithms have been studied extensively in the literature [3]–[6].

The ALOHA protocol was first developed for random access in packet radio networks. To improve efficiency, a modification of ALOHA, known as slotted ALOHA, was developed. This improvement results in a doubling of the achievable throughput. The advantage of the slotted ALOHA protocol is that it is very simple. The terminals transmit their packets as they become ready for transmission, and if there is a collision, they simply retransmit. The disadvantage of the slotted ALOHA protocol is its slow throughput under heavy traffic load conditions. With high traffic loads, ALOHA protocols become inefficient, since the contention between all mobile stations exposes most of the offered traffic to collisions, and thus results in multiple retransmissions and increase delays.

To improve the system stability, the framed ALOHA was developed [7], [8]. In [9], Schoute analyzed the performance of the dynamic frame length ALOHA, in which the frame length is adjusted dynamically. The author also proposed the *a posteriori* expected value of 2.39 to estimate the backlog (the number of mobiles that must still transmit their packets). The expected value is exact only if the *a priori* distribution of the backlog is Poisson with an integer valued mean. The author claimed that the dynamic frame length ALOHA could achieve a throughput of 0.426, which is higher than the upper bound (about 0.368) of ordinary slotted ALOHA. We think this high throughput can be regarded as a special case where the frame length is set to one and the backlog must satisfy a specific Poisson distribution. Also, the throughput is calculated based on the inverse of the weighted mean of the number of timeslots needed. The weights are the Poisson probabilities for the first eight possible entries.

Manuscript received March 27, 2007. First published June 10, 2008; current version published December 30, 2008. This paper was recommended for publication by Associate Editor P. Cole and Editor N. Viswanadham upon evaluation of the reviewers' comments.

The author is with the Institute of Telecommunications Management, National Cheng Kung University, Tainan, Taiwan, R.O.C. (e-mail: wtchen@mail.ncku.edu.tw).

Digital Object Identifier 10.1109/TASE.2008.917093

1545-5955/$25.00 © 2008 IEEE

However, the throughput is typically defined as the number of successful transmission packets divided by the number of slots needed.

The dynamic frame length ALOHA can also be used to deal with anticollision problems in an RFID system and has been widely adopted in some RFID standards, such as ISO 18000–6 and ISO 14443–3 [10]–[12]. In [13], Vogt presented an anticollision scheme using the dynamic frame length ALOHA. His scheme was implemented in the "I-code" system developed by Philips Semiconductors. The author proposed an estimate function using the distance between the read result and the expected value vector to estimate the tag quantity. He also used the Markov process to model the read process and suggested a set of dynamic frame lengths in the read process. Through use of the Markov model, he computed a lower bound of the number of reading steps necessary to identify all tags. Since any suggested frame length is subject to the specifications of the I-code system, available frame lengths are limited to powers of 2. This limitation results in lower throughput. In fact, maximum throughput can only be achieved if the frame length is set to the number of tags that need to be read [14].

In [15], the authors adopted Vogt's tag estimate method and derived the dynamic frame length for achieving maximum channel efficiency. From their derivations, they claimed that if the frame length approximately equals the number of tags plus one, the maximum channel efficiency can be obtained. In addition, they also proposed a Modulo operation to group a large number of tags. Results showed that if the number of unread tags is slightly larger than 354, the grouping operation is useful to improve channel efficiency.

Cha and Kim [16] and Floerkemeier [17] proposed tag estimate methods for RFID anticollision using framed ALOHA. These methods are based on Schoute's analysis [9] for dynamic frame length ALOHA. If the frame length is assumed to be the number of tags, the expected value of collision tags is $2.39C$, where C is the number of collision slots. However, this assumption is difficult to confirm in practice. Thus, using the expected value to estimate tag quantity may cause significant error and increase read delay.

In [18], the authors also used the expected value of 2.39 to estimate the backlog. Although the dynamic frame length ALOHA is employed, the frame length is adjusted only when the estimated number of tags is greater than 1.15 times the quantity presented in the previous cycle. When the frame length is adjusted, the new frame length is set based on a specific mapping rather than the optimal frame length.

In this paper, we present a new tag estimate method to improve performance of the RFID anticollision algorithm based on dynamic frame length ALOHA. Unlike previous studies in which tag quantity is estimated based on the expected value of empty slots, successful transmission slots, or collision slots, our method is based on *a posteriori* probability distribution. We derive the exact *a posteriori* probability distribution and propose a decision rule for tag estimate, named the maximum *a posteriori* probability rule. The performance of the different tag estimate method is compared.

We also derive the optimal frame length by maximizing channel usage efficiency. When the dynamic frame length ALOHA is implemented, we assume the optimal frame length can be set to any discrete values less than the available maximum. Note that a constraint on available frame length results in worse performance, as described earlier in this section. In addition, we study the effect of initial frame length on the uplink throughput of radio channel. Extensive simulations are performed to examine the proposed method's performance.

II. Overview of Dynamic Frame Length ALOHA Anticollision

In this section, we first describe why the dynamic frame length ALOHA is more suitable for improving performance of the RFID anticollision than the standard slotted ALOHA. One of the key advantages for the dynamic frame length ALOHA is that mobile nodes require only limited capabilities. Also, with a powerful base station or reader, the framed ALOHA can dynamically adjust the frame length according to traffic loads and, therefore, enhance channel usage efficiency. In an RFID system, the reader can dominate the multiple-access procedure, including initiating communication, controlling read process, and receiving responses from tags. Tags are, in general, passive devices and have very limited power. In real-life RFID applications, the tag quantity that needs to be read simultaneously is not very high, and each tag transmits only a small amount of data once in a read process. Hence, the dynamic frame length ALOHA is suitable for RFID systems.

In a dynamic frame length ALOHA anticollision algorithm, the reader initiates a read cycle by broadcasting a request command to all tags under its coverage. This request command also includes a dynamic parameter L, called the frame length, by which each tag randomly selects one of the available time slots and transmits its ID at the selected time slot. For a given time slot, there are only three possible outcomes: idle, successful transmission, and collision. The channel is idle if no tag transmits its ID in the time slot. A successful transmission means one tag only sends its ID. If two or more tags transmit in the same time slot, the reader suffers from collision and no tag can be read. After a read cycle, the reader can observe E empty slots, S singly occupied (or successful) slots, and C collision slots, where $E+S+C=L$. If the number of collision slots is greater than zero, the reader needs to estimate the number of tags that are present at the beginning of the read cycle according to the triple (E, S, C) and then to forecast the number of unread tags by subtracting the number of singly occupied slots S. According to the number of unread tags, the reader then determines an appropriate frame length for the next read cycle. The read process stops when there is no collision in the read cycle.

Consider a frame length L. In the presence of a large amount of collision slots, it is reasonable to assume that the number of tags is great. In this case, the number of empty slots should be very small. In contrast, a large amount of empty slots means that just a few tags are present. Due to the constraint of $E+S+C=L$, we can use any three parameters to estimate tag quantity.

An example presented in Fig. 1 illustrates the process of the anticollision scheme adopting the dynamic framed ALOHA protocol. In this example, we assume there are four tags which need to be read, and the initial frame length is 4. In the first read cycle, the reader sends a request command together with an argument 4 as the frame length. Tags 1 and 3 transmit their ID

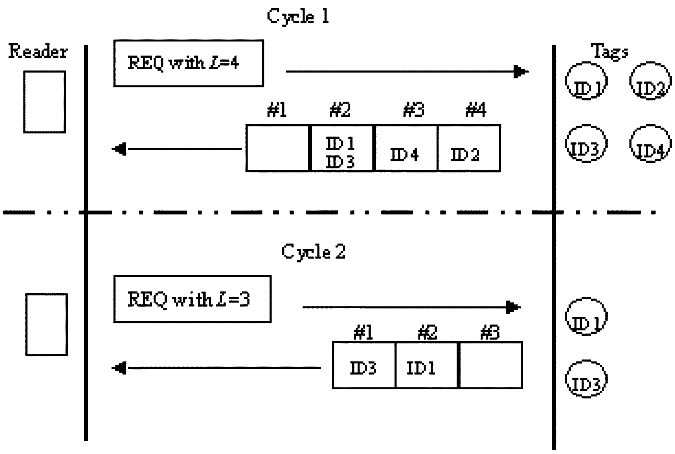

Fig. 1. Anticollision process with dynamic framed ALOHA.

in time slot 2. The transmissions cause a collision because they occur at the same time slot. Tags 2 and 4 send their ID in slots 4 and 3, respectively, and thus can be successfully identified by the reader because the two slots are singly occupied. Since a collision occurs in time slot 2, this implies there are at least two tags which need to be read. Hence, another read cycle is required. In the second cycle, the reader determines a new frame length 3 and broadcasts it by a request command. Finally, the reader completes the reading of all tags because no collision occurs in this cycle.

Analysis for the anticollision problem can be divided into two primary parts. The concern of the first part is how to precisely estimate the number of tags according to the information of idle, collision, and successful transmission. Since at least two tags are involved in a collision, a low bound measure $S + 2C$ can be used to estimate the number of tags. However, more precise estimates are required to improve tag estimate performance. The other part involves determination of an appropriate frame length to achieve maximum throughput or channel efficiency after the reader forecasts the number of tags. Both parts will affect the anticollision protocol's performance.

Note that the frame length of the first read cycle will affect the performance of the anticollision algorithm. In practice, the number of tags is usually not known before the read process is started. Since a small initial frame length can cause large numbers of collisions, more time slots are required to read all tags when the number of tags is extremely high. In contrast, a large initial frame length will result in more idle time slots and increased waste of uplink channel bandwidth when the number of tags is small. The effect of initial frame length on anticollision performance will be discussed later.

III. Tag Estimate

Consider n tags are to be read and a read cycle with a frame length of L time slots. Given one of the time slots, the number of tags allocated in the slot is a binomial distribution with n Bernoulli experiments and $1/L$ occupied probability. The probability of finding r tags in the slot is therefore given by

$$B(r) = \binom{n}{r}\left(\frac{1}{L}\right)^{r}\left(1-\frac{1}{L}\right)^{n-r}. \tag{1}$$

Accordingly, we obtain the probabilities of empty, successful transmission, and collision for the slot as

$$p_e = B(0) = \left(1-\frac{1}{L}\right)^{n} \tag{2}$$

$$p_s = B(1) = \frac{n}{L}\left(1-\frac{1}{L}\right)^{n-1} \tag{3}$$

$$p_c = 1 - p_e - p_s. \tag{4}$$

Next, we need to derive the probability of finding the exact E empty slots, S singly occupied slots, and C collision slots if there are L slots. The problem can be modeled as a multinomial distribution with L repeated independent trials, where each trial has one of three outcomes: empty, successful, or collision. Suppose that the possible outcome in each trial is p_e for empty, p_s for successful, and p_c for collision. In general, the probability is subject to the condition $p_e + p_s + p_c = 1$. The probability that in L trials, empty outcome occurs E times, successful outcome occurs S times, and collision outcome occurs C times is

$$P(E,S,C) = \frac{L!}{E!S!C!}p_e^E p_s^S p_c^C. \tag{5}$$

In fact, the probability is the general term of the multinomial expansion of $(p_e + p_s + p_c)^L$.

Therefore, for a read cycle with frame length L, we have *a posteriori* probability for the number of tags n when E empty slots, S singly occupied slots, and C collision slots are observed, as follows:

$$\begin{aligned} P(n|E,S,C) = {} & \frac{L!}{E!S!C!} \\ & \times \left[\left(1-\frac{1}{L}\right)^{n}\right]^{E}\left[\frac{n}{L}\left(1-\frac{1}{L}\right)^{(n-1)}\right]^{S} \\ & \times \left[1-\left(1-\frac{1}{L}\right)^{n}-\frac{n}{L}\left(1-\frac{1}{L}\right)^{(n-1)}\right]^{C}. \end{aligned} \tag{6}$$

Based on the *a posteriori* probability distribution, we attempt to determine tag quantity such that the probability is maximized. Hence, the decision rule of our proposed tag estimate method is as follows:

Set the tag estimate $\hat{n} = n,$ if $P(n|E,S,C)$ is maximum.

This decision rule can be referred to as the maximum *a posteriori* probability rule.

The *a posteriori* probability distribution is of primary concern for us to estimate tag quantity when we know the frame length (L) and transmission outcomes (E, S, and C) in a read cycle. It is straightforward to estimate the tag quantity such that the *a posteriori* probability reaches its maximum value.

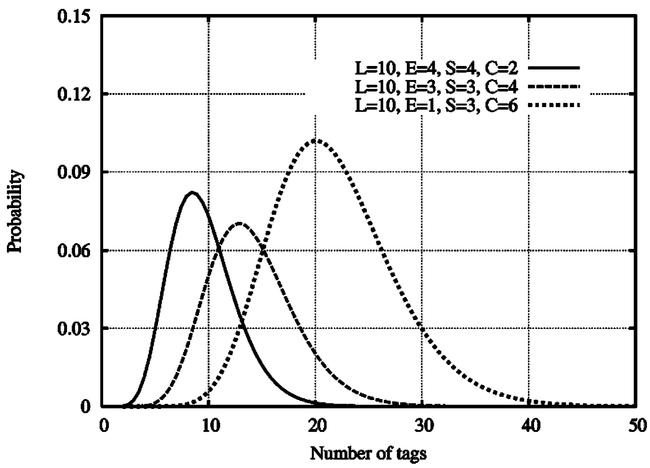

Fig. 2. *A posteriori* probability distribution for number of tags.

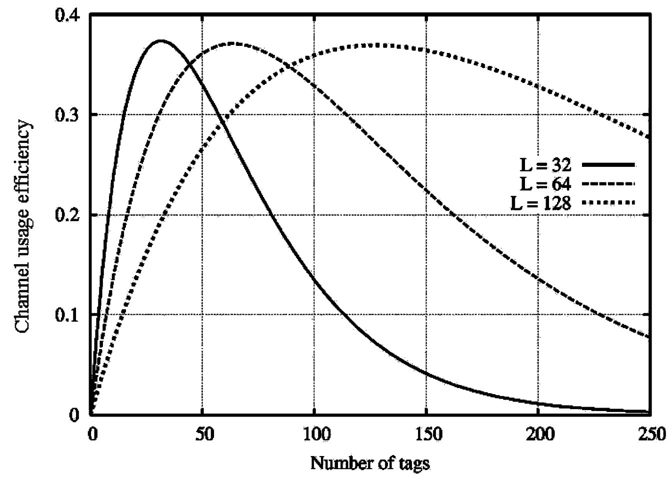

Fig. 3. Channel usage efficiency as function of tag quantity.

TABLE I
TAG ESTIMATES FOR PROPOSED METHOD ($L = 10$)

C \ S	0	1	2	3	4	5	6	7	8	9
1	3	3	4	5	6	7	8	9	10	11
2	5	6	7	8	9	10	11	12	13	-
3	7	8	9	10	11	12	13	14	-	-
4	10	11	12	13	14	15	16	-	-	-
5	12	14	15	16	17	19	-	-	-	-
6	16	17	19	20	22	-	-	-	-	-
7	20	22	23	25	-	-	-	-	-	-
8	26	28	30	-	-	-	-	-	-	-
9	35	38	-	-	-	-	-	-	-	-
10	195	-	-	-	-	-	-	-	-	-

Note that *S*+*C*+*E*=*L*.

Fig. 2 presents the *a posteriori* probability distribution versus the number of tags n. The frame length is set to 10. Maximum probability occurs at $n = 9$ for $E = 4$, $S = 4$, and $C = 2$, at $n = 13$ for $E = 3$, $S = 3$, and $C = 4$, and at $n = 20$ for $E = 1$, $S = 3$, and $C = 6$. Hence, we estimate the number of tags as nine, if the frame length is ten and the reader observes four empty slots, four singly occupied slots, and two collision slots after completing a read cycle. Tag estimates for all possible triples (E, S, C) can be obtained through prior computations.

Table I shows the tag estimates for $L = 10$. Note that when the number of collisions equals the frame length (ten slots in this case), we have an extremely high estimate (195 tags) for actual tag quantity. This case corresponds to the most crowded situation, because both the number of empty slots and the number of singly occupied slots are zero. Note also that, in Table I, a dash (–) is placed in some cells where $S+C+E = L$ is not satisfied, for example, in the cell corresponding to $C = 9$ and $S = 2$.

To measure the performance of the proposed tag estimate method, we define the estimate error as

$$\text{error} = \frac{|n - \hat{n}|}{n} \tag{7}$$

where $\hat{n}$ is the estimate for tag quantity.

IV. DYNAMIC FRAME LENGTH

After obtaining the estimate of actual tag quantity, the reader can then forecast the number of unread tags by subtracting the number of successful slots from the above estimate. The reader also needs to determine an optimal frame length for the next read cycle. On the one hand, a too small frame length increases collision probability. Plenty of retransmissions are then required and this results in inefficient performance. On the other hand, a too large frame length may produce a large number of idle slots and thus decrease channel throughput. Appropriate frame length can be derived from either throughput or channel usage efficiency. As regards wireless communication networks, throughput performance of the framed ALOHA has been investigated in [14]. Results indicate maximum throughput is 36.8% when frame length equals the number of mobile nodes. It is highly expected that framed ALOHA anticollision performance in an RFID system will produce the same result. In this section, we propose a method for deriving the optimal frame length from channel usage point of view.

First, consider n tags are to be read. We need to determine an appropriate frame length for achieving maximum channel efficiency. As mentioned in the previous section, the number of tags allocated in a given time slot is a binomial distribution. Further, the probability of finding a single tag is modeled by (3). With a total of L slots, the expected value of the number of singly occupied slots is

$$E[S] = n\left(1 - \frac{1}{L}\right)^{n-1}. \tag{8}$$

Channel usage efficiency is defined as the expected value of the number of singly occupied slots divided by frame length

$$U = \frac{E[S]}{L} = \frac{n}{L} \cdot \left(1 - \frac{1}{L}\right)^{n-1}. \tag{9}$$

In order to maximize channel usage efficiency, we take the first derivative of U with respect to L. Let the derivative equal zero, we then have

$$\frac{dU}{dL} = \frac{n(n-L)(L-1)^{n-2}}{L^{n+1}} = 0. \tag{10}$$

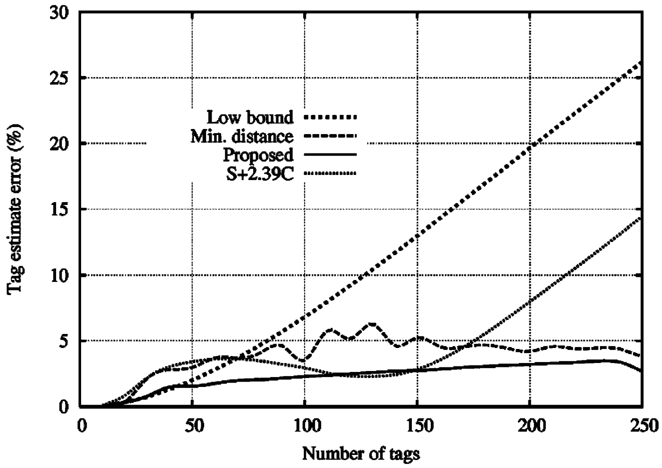

Fig. 4. Simulation results for tag estimate error.

Maximum utility efficiency therefore occurs at $L = n$ or $L = 1$. Frame length L, in practice, is greater than one in order to accommodate multiple tags. Hence, optimal frame length is equal to the number of tags. In addition, we examine the second-order derivative of U. We find its value is negative when $L = n$. This negative value ensures the extreme value of U at $L = n$ is a maximum rather than a minimum.

Fig. 3 shows channel usage efficiency as a function of the number of tags for different frame lengths. Each curve has a maximum value equal to approximately $0.368(e^{-1})$ when the number of tags equals the frame length. These maximum values are very close to the theoretical maximum throughput for the uplink channel of framed ALOHA.

Our RFID anticollision procedure is summarized as follows:

```
dynamicALOHA() {
L = 128;    // initial frame length
cycle_counter = 0;
do {
cycle_counter ++;
[E, S, C] = performReadCycle(L);
// Each tag selects a slot from L.
// The reader counts empty, successful,
// and collision slots.
n_estimate = performTagEstimate(L, E, S, C);
// estimate tag quantity
L = n_estimate-S;    // set a new frame length
} while (C! = 0)
// repeat read process if collisions occur
}
```

V. Results

The proposed tag estimate method's performance was examined carrying out extensive simulations based on the Monte Carlo technique. Frame length was set to 128 slots in our simulations and n tags, for example 30, were put into the 128 time slots 10 000 times in order to ensure convergence of simulation results. After each experiment, we obtained a triple (E, S, C), and then performed the tag estimate according to the proposed method. The estimate error was also computed using (7). Finally, we obtained the average estimate error after completing 10 000 experiments.

TABLE II
Frame Lengths Suggested By Vogt for Tag Number Intervals

N slots	1	4	8	16	32	64	128	256
Low	-	-	-	1	10	17	51	112
High	-	-	-	9	27	56	129	∞

Fig. 4 presents simulation results for tag estimate error. Results indicate the *proposed* method has an estimate error of no more than 4%. The use of a low bound measure in tag estimates, however, causes higher error, especially when the number of tags is very large. For example, the low bound estimate error reaches 20% if tag quantity is 200. The low bound method represents a conservative but simple estimate. The estimate function of $S + 2.39C$ has a very low estimate error when the number of tags equals approximately the frame length 128 used here. When the number of tags differs substantially from the frame length, using the function $S + 2.39C$ to estimate tag quantity results in higher error. This is because the estimate function is based on the assumption that traffic load (the number of tags in this case) equals the frame length. Fig. 4 also shows the tag estimate performance of Vogt's method. His method can achieve an estimate error lower than 6%. From the results, we observe our proposed tag estimate method is more precise than Vogt's method. We believe the considerably lower estimate error of the proposed tag estimate method can increase the performance of framed ALOHA anticollision in an RFID system.

Note that the estimation function for the low bound method is $S+2C$; the estimation function used by Vogt is as follows [13]:

$$\varepsilon_{vd}(L, E, S, C) = \min_{n} \left| \begin{pmatrix} a_0 \\ a_1 \\ a_m \end{pmatrix} - \begin{pmatrix} E \\ S \\ C \end{pmatrix} \right| \tag{11}$$

where a_0, a_1, and a_m are the expected values of the number of empty slots, singly occupied slots, and collision slots, respectively. The expected value of the number of singly occupied slots is described in (8). The expected values of the number of empty slots and collision slots are

$$a_0 = L \cdot B(0) = L\left(1 - \frac{1}{L}\right)^n \tag{12}$$

$$a_m = L - a_0 - a_1. \tag{13}$$

Vogt's method can be referred to as the minimum distance method which is similar to the minimum message length method developed by Wallace [19], [20]. Note that Wallace's method is a general metric since 1968, on lines of Shannon Entropy, etc.

Next, we turn our attention to the effect of frame length on total time slots required to read tags. The total time slot is the sum of the numbers of empty occupied slots, singly occupied slots, and collision slots in a read process. We compare the performance of a framed ALOHA algorithm, which uses optimal

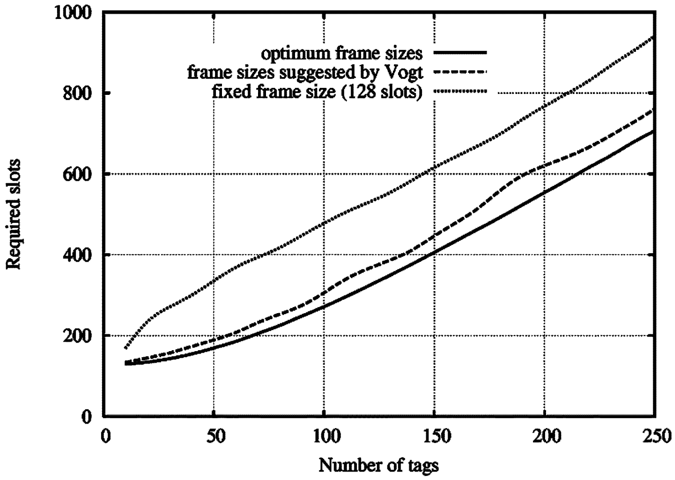

Fig. 5. Influence of frame length on time slots required to read all tags.

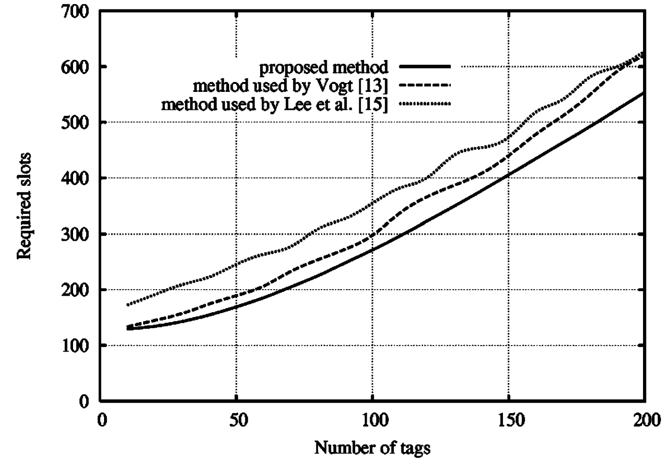

Fig. 6. Simulation results for time slots required to read all tags.

frame length, with the performance of a framed ALOHA algorithm, which uses the frame length suggested by Vogt. As described in Section IV, optimal frame length equals the number of tags that needs to be read. The frame length suggested by Vogt is listed in Table II [13]. Fig. 5 presents a comparison of the two frame length selections. In our simulation, we use the maximum *a posteriori* probability rule to estimate tag quantity and assume the number of tags is no more than 256. Since the number of tags which needs to be read in practice is unknown, we set the initial frame length to the middle value of 128. From Fig. 5, we find using the optimal frame length leads to fewer total time slots required to complete tag reading, compared with using the frame length suggested by Vogt. Fig. 5 also presents the required slots for static framed ALOHA with a fixed frame length of 128 slots. Due to the lack of dynamic adjustment for frame length, the static framed ALOHA requires more empty slots and results in more read delay than the dynamic frame length ALOHA.

In Fig. 6, we compare the read performance of our anticollision algorithm with that of other algorithms, including Vogt's [13] and Lee's [15]. Initial frame length is set to 128 slots in this case. For our proposed algorithm, we employ our proposed tag estimate method and the optimal frame length we have derived. We find from Fig. 6 that of the three algorithms, our method requires fewest time slots to read a set of tags. Since our proposed algorithm has very high tag estimate accuracy and adopts the optimal frame length in each read cycle, our method achieves better performance than the other methods.

The initial frame length also affects the anticollision algorithm's performance. Fig. 7 shows uplink throughput for different initial frame lengths. Normalized throughput, defined as the number of tags divided by the required total time slots, can be used to measure the radio channel's performance. The maximum *a posteriori* probability method for tag estimate and optimum frame length are adopted in this simulation. We find that if the number of tags is greater than the initial frame length, throughput decreases slowly and converges to 0.35. When the number of tags is less than the initial frame length, throughput decreases rapidly.

As can be seen in Fig. 7, maximum throughput occurs when the initial frame length is equal to the number of tags which needs to be read. For example, if the initial frame length is 32, throughput reaches a maximum when tag quantity is also equal to 32. We also observe that maximum values are almost equal to 0.368, which is the theoretical maximum throughput of the framed ALOHA applied in wireless local area networks.

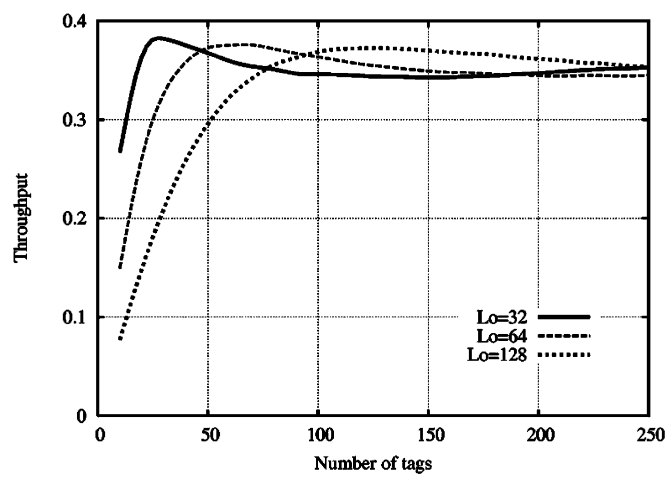

Fig. 7. Influence of initial frame length on normalized throughput.

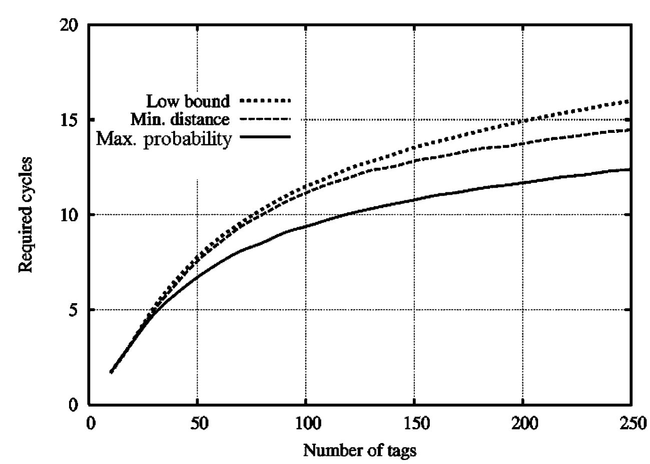

Fig. 8. Simulation results for cycles required to read all tags.

In addition to total time slots, anticollision performance depends on the total cycles required to complete the identification of all tags. If more cycles are required, this means the system spends more time dealing with the communication handshaking process between the reader and tags. Fig. 8 presents a comparison of average total cycles for the three tag estimate methods. The optimal frame length is used in this comparison. The maximum *a posteriori* probability method requires fewer read cycles. This is because this method is more accurate than the other two for estimating.

VI. Conclusion

A more accurate tag estimate method for solving the anti-collision problem in RFID systems using framed ALOHA has been proposed. The exact *a posteriori* probability distribution for the number of tags has been derived. Based on the maximum *a posteriori* probability decision rule, the tag estimate for all possible reading outcomes can be computed and stored in the reader's memory. Since a reader, in general, has sufficient memory, such prior operations can be easily carried out. From the results presented in Section V, it can be seen that our tag estimate method has an estimate error less than 4%. Use of our proposed tag estimate method together with the optimal frame length requires fewer time slots and read cycles. Although the initial frame length affects throughput performance, our proposed method can achieve an uplink throughput of 0.35 if the actual tag quantity is not much greater than the initial frame length.

The results of our analysis suggest that the constraint on frame length can be removed and optimal frame length can be adopted for channel efficiency improvement. To increase the accuracy of tag estimate, one may take all available information into consideration, for example, the parameters, L, E, S, and C, when estimating tag quantity. In addition, based on our reading of the two RFID standards ISO 18000-6 and ISO 14443-3, the frame length update mechanism, including tag estimate method and the setting of frame length, is not specified. Our method can become a suitable candidate for such a mechanism and can be useful for engineers to implement the dynamic frame length ALOHA algorithm in a real RFID system.

References

[1] K. Finkenzeller, *RFID Handbook*, 2nd ed. New York: Wiley, 2003.
[2] D. R. Hush and C. Wood, "Analysis of tree algorithm for RFID arbitration," in *Proc. IEEE Int. Symp. Information Theory*, 1998, pp. 107–107.
[3] J. Myung, W. Lee, and J. Srivastava, "Adaptive binary splitting for efficient RFID tag anti-collision," *IEEE Commun. Lett.*, vol. 10, no. 3, pp. 144–146, Mar. 2006.
[4] M. A. Kaplan and E. Gulko, "Analytic properties of multiple-access trees," *IEEE Trans. Inform. Theory*, vol. IT-31, no. 1, pp. 255–263, Mar. 1985.
[5] C. Law, K. Lee, and K.-S. Siu, "Efficient memoryless protocol for tag identification," in *Proc. 4th ACM Int. Workshop Discrete Algorithms and Methods for Mobile Computing and Communications*, Aug. 2000, pp. 75–84.
[6] M. Nanjundaiah and V. Chaudhary, "Improvement to the protocol specification for 900MHz class 0 radio frequency identification tag," in *Proc. 19th Int. Conf. Advanced Information Networking and Applications*, 2005, vol. 2, pp. 616–620.
[7] W. Szpankowski, "Packet switching in multiple radio channels: Analysis and stability of a random access system," *Comput. Network*, vol. 7, pp. 17–26, 1983.
[8] J. E. Wieselthier, A. Ephremides, and L. A. Michaels, "An exact analysis and performance evaluation of framed ALOHA with capture," *IEEE Trans. Commun.*, vol. 37, no. 2, pp. 125–137, Feb. 1989.
[9] F. C. Schoute, "Dynamic frame length ALOHA," *IEEE Trans. Commun.*, vol. 31, no. 4, pp. 565–568, Apr. 1983.
[10] Class 1 Generation 2 UHF Air Interface Protocol Standard EPCglobal, 2005.
[11] Parameters for Air Interface Communications at 860 MHz to 960 MHz Information Technology—Radio Frequency Identification for Item Management, 2004, ISO/IEC 18000-6, Part 6.
[12] Initialization and Anticollision Identification Cards—Contactless Integrated Circuit Cards—Proximity cards, 2000, ISO/IEC 14443-3, Part 3.
[13] H. Vogt, "Efficient object identification with passive RFID tags," in *Proc. Int. Conf. Pervasive Computing*, 2002, pp. 98–113.
[14] L. Roberts, "Extensions of packet communication technology to a hand held personal terminal," in *Proc. Spring Joint Computer Conf.*, 1972, pp. 295–298.
[15] S.-R. Lee, S.-D. Joo, and C.-W. Lee, "An enhanced dynamic framed ALOHA algorithm for RFID tag identification," in *Proc. Int. Conf. Mobile and Ubiquitous Systems: Networking and Services*, 2005.
[16] J.-R. Cha and J.-H. Kim, "Novel anti-collision algorithms for fast object identification in RFID system," in *Proc. Int. Conf. Parallel and Distributed Systems Computing*, 2005, vol. 2, pp. 63–67.
[17] C. Floerkemeier, "Transmission control scheme for fast RFID object identification," in *Proc. Int. Conf. Pervasive Computing Communications Workshops*, 2006.
[18] B. Zhen, M. Kobayashi, and M. Shimizu, "Framed ALOHA for multiple RFID objects identification," *IEICE Trans. Commun.*, vol. E80-B, no. 3, pp. 991–999, Mar. 2005.
[19] C. S. Wallace and D. M. Boulton, "An information measure for classification," *Computer J.*, vol. 11, no. 2, pp. 185–194, 1968.
[20] C. S. Wallace and D. L. Dowe, "Minimum message length and Kolmogorov complexity," *Computer J.*, vol. 42, no. 4, pp. 270–283, 1999.

Wen-Tzu Chen received the M.S. degree in electrical engineering from National Taiwan University, Taipei, in 1989, and the Ph.D. degree in electrical engineering from National Cheng Kung University, Tainan, in 1999.

From 1993 to 1995, he was with National Education Radio as an Audio and RF Engineer. He joined the Directorate General of Telecommunications, Ministry of Transportation and Communications, Taiwan, 1997 to 1999, working on spectrum management, frequency assignment, and radio-frequency interference. He is currently an Associate Professor at the Institute of Telecommunications Management, National Cheng Kung University, Tianan. His research interests include mobile communications systems and applications, wireless network, RF engineering, and spectrum management.