An Efficient Framed-Slotted ALOHA Algorithm with Pilot Frame and Binary Selection for Anti-Collision of RFID Tags

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***Abstract*—Reducing the number of tag collisions is one of the most important issues in RFID systems, as collisions induce inefficiency. This paper presents a mechanism of grouping of tags via a bit mask, quick tag estimation by a pilot frame and near optimal binary tree-based collision resolution with a frame. Performance analysis and simulation results show that the proposed anti-collision algorithm consumes fewer time slots as compared to previous work, and approaches to the case with the optimal frame size using binary tree collision resolution.**

***Index Terms*—Anti-collision, collision threshold, pilot frame, RFID, tag estimation, tag identification.**

I. Introduction

AMong ALOHA-based RFID protocols [1], Framed-Slotted ALOHA (FSA) is the most popular. It reduces the probability of tag collision by letting each tag send its responding signal in a random time slot in a frame. If, however, the difference between the number of the tags and the frame size is large, the throughput of FSA becomes low. This necessitates the design of more sophisticated random access mechanisms that rely on the reader's ability to estimate the number of tags in order to decide on the frame size, for example Dynamic FSA (DFSA) [3] or Adaptive Slotted ALOHA Protocol (ASAP) [6].

In tree-based RFID protocols [2], if a collision occurs in a slot, the collided tags are randomly separated into two subgroups by using a binary tree protocol until all tags are identified. If the number of tags is small, tree-based protocols have reasonable performance. When the number of tags is large, however, at the early stage, they may experience poor performance because time slots might be wasted due to many collision slots until all tags are identified. Once again, some of these wasted time slots can be eliminated by judicious partitioning of the tags and construction of the binary tree at the expense of added complexity [7].

FSA with robust Estimation and Binary selection (EB-FSA) [5] creates an appropriate frame based on the robust estimation of tags and handles collisions in the frame by a binary tree protocol. Though this protocol shows a noticeable improvement, it still requires extra frames for appropriate estimation of the number of tags. In this paper, we propose a new RFID anti-collision algorithm, Framed-Slotted ALOHA with small Pilot frame and Binary selection (FSAPB), for efficient tag identification that overcomes these concerns.

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II. The Proposed Algorithm: FSAPB

In the proposed FSAPB, the tags that respond to a reader are divided into M subgroups by using bit masks. A pilot frame of length L_p slots is used in the estimation of the frame size for the identification of the first subgroup. Grouping the tags into small subgroups by bit masks reduces L_p, which saves time slots for tag estimation. After tags in the first subgroup transmit their IDs at randomly selected time slots in L_p, the reader counts the number of collision slots, c, estimates the collision probability as $\hat{P}_{coll} = L_p^{-1} \max(0, c - 1/2)$ and compares this value to the collision threshold P_{th}.

If $\hat{P}_{coll}$ is greater than P_{th}, only a single identification frame is needed. When the number of tags is n_1 and the frame size is L_p, the collision probability is

$$P_{coll} = 1 - \left(1 - \frac{1}{L_p}\right)^{n_1} - n_1 \cdot \frac{1}{L_p}\left(1 - \frac{1}{L_p}\right)^{n_1 - 1}. \quad (1)$$

Assuming $\hat{P}_{coll} = P_{coll}$ and given L_p, the approximate number of tags n_1 can be found from Eq. (1) and the scheme in [5]. When $\hat{P}_{coll}$ is high, the identification frame size L_1 is estimated as n_1 minus the number of identified tags in L_p. In the frame L_1, the reader conducts the identification of the collided tags during L_p by the binary tree protocol.

On the other hand, if $\hat{P}_{coll}$ is lower than P_{th}, only a small number of collisions is observed and the binary tree protocol can be directly applied at the additional slots L_{add} after the end of the pilot frame without further frames. The tags that collided during L_p now come to have new random counter values according to the order of collisions during L_p and the remaining slots in L_p in order to be resolved during L_{add}.

In the remaining subgroups partitioned by bit masks, one can estimate the number of tags without further pilot frames, because the bit mask partitions tags uniformly among subgroups assuming uniform distribution of tags. So, a suitable frame size L_k required for the identification of the kth subgroup is computed from the number of tags identified in the previous subgroup. That is, L_k is decided by multiplying a certain constant γ by the number of tags n_{k-1} estimated in the previous subgroup $k-1$. In the sequel, we will see why this is the case. During L_k, if a collision occurs, collided tags are resolved by the binary tree protocol. This identification step is repeated from the 2nd subgroup to the Mth subgroup.

Fig. 1 shows an example of the identification process of the FSAPB algorithm. During L_p, the tags of the first subgroup have random counter values and the counter values are decremented by one at every non-collision slot. A tag transmits its ID to the reader when its random counter value becomes 0. If a collision occurs, the collided tags select new random counter values from 0 or 1 plus offset so that they are resolved by the binary tree protocol during L_{add} or L_1 depending on whether $\hat{P}_{coll}$ is less than P_{th} or not. In Fig. 1 (a), the pilot frame decides that the measured $\hat{P}_{coll}$ is less than P_{th}, so L_{add} is used for tag identification. In Fig. 1 (b), with the activity of the pilot frame, it decides that $\hat{P}_{coll}$ is greater than P_{th}, a frame L_1 for identification of the tags not identified in L_p is used. During L_{add} or L_1, if a collision occurs, the collided tags select new random counter values according to the binary tree protocol and all tags other than the collided tags increase their counter values by 1. If there is no collision in a slot, all tags decrease the counter values by 1. Tags transmit IDs when their counter values become 0. Collisions are successively resolved by such binary tree protocol. From the 2nd subgroup to the Mth subgroup, the pilot frame is not used but L_k is used and the binary tree protocol operates directly for the collided tags.

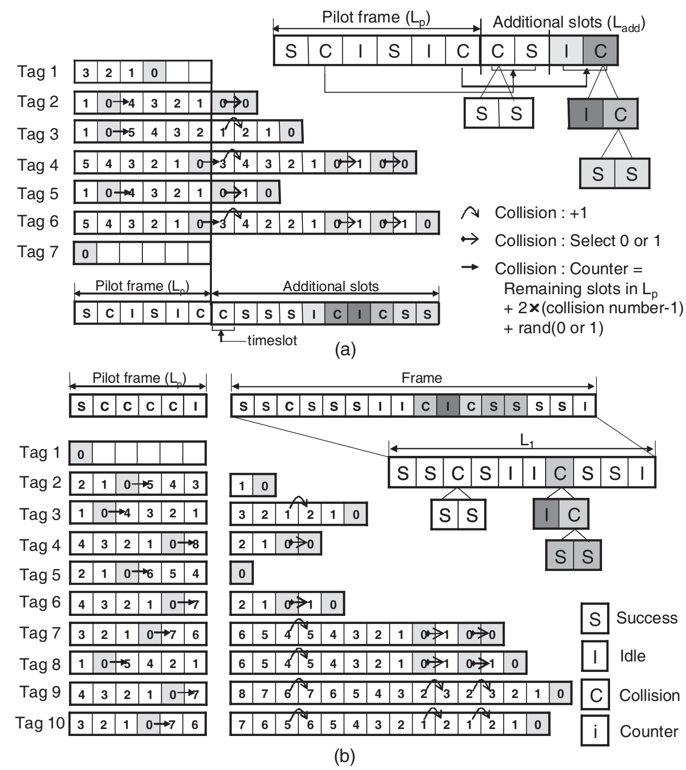

Fig. 1. An example of the proposed FSAPB algorithm, when $\hat{P}_{coll}$ is (a) less and (b) greater than P_{th} (identification of the 1st subgroup).

III. Performance Analysis

A. FSAPB with the Single Frame

Let n, r and L be the number of tags, the number of tags transmitted in a time slot and the size of a frame, respectively. Let Y_i^r the Bernoulli random variable if r tags transmit in slot i. Then, the expected number of time slots in which r tags transmit can be approximated by [1]

$$E_r^n(L)=E\left[\sum_{i=1}^{L} Y_i^r\right] = \binom{n}{r}\left(\frac{1}{L}\right)^r\left(1-\frac{1}{L}\right)^{n-r} L, \quad 0\leq r\leq n. \tag{2}$$

Let $\overline{F_r^m}$ be the expected number of splits for identification of r collided tags in an m-ary split [4]. Then,

$$\overline{F_r^m} = 1 + \sum_{i=1}^{\infty} c_r(m^i), \tag{3}$$

$$c_r(m^i) = m^i\left[1-\left(1-\frac{1}{m^i}\right)^r\right] - r\left(1-\frac{1}{m^i}\right)^{r-1}, \tag{4}$$

$$\alpha_r(m) = m \times \overline{F_r^m}, \qquad 2\leq r\leq n. \tag{5}$$

where $c_r(m^i)$ denotes the expected number of contention slots at level i of m-ary collision tree when r tags transmit. Eq. (3) shows how many expected number of splits are required until the collided r tags in a particular slot are resolved. And the average number of required slots to resolve r collided slots is $\overline{F_r^m}$ multiplied by m since each m-ary split consists of m slots. One can obtain the value of $\alpha_r(m)$ for varying numbers of r and m. In the binary tree protocol, the value of m is 2.

When n and L are known, the total average number of required time slots $T(n)$ is derived from Eqs. (2)-(5) by adding the size of the frame L and the extra slots to resolve collisions occurred in L by the binary tree protocol. Noting $\alpha_0(2) = 0$, $\alpha_1(2) = 0$ and $\sum_{r=0}^{n} E_r^n(L) = L$,

$$T(n)= L+\sum_{r=2}^{n} E_r^n(L)\cdot\alpha_r(2) = \sum_{r=0}^{n}(E_r^n(L)\cdot(\alpha_r(2)+1)). \tag{6}$$

In general, performance of FSA is known to be optimal if the frame size L equals the number of tags n [4]. In each subgroup of our FSAPB with the single optimal frame using tree-based protocol for collision resolution, when the number of tags n is given, the optimal frame size L_{opt} needs to be calculated. With $L = 1/p$, Eq. (6) is transformed by making use of the identities, $\sum_{r=0}^{n}\binom{n}{r}a^r b^{n-r} = (a+b)^n$ and $\sum_{r=0}^{n}\binom{n}{r}ra^{r-1}b^{n-r} = n(a+b)^{n-1}$ with $a = p$ and $p(1-2^{-i})$, respectively, and $b = 1-p$. After substituting $p = 1/(\gamma n)$, dividing by n, taking the limit $n\rightarrow\infty$, and using the Euler-Maclaurin formula [8] for the summation in the $\alpha_r(2)$ term, we obtain

$$\lim_{n\rightarrow\infty}\frac{T(n)}{n} \approx 2\gamma-(\gamma+1)e^{-1/\gamma}+\frac{2}{\ln(2)}(1-\gamma(1-e^{-1/\gamma})) - \frac{\ln(2)}{6}\left(\gamma(1-e^{-1/\gamma})-\frac{1+\gamma}{\gamma}e^{-1/\gamma}\right). \tag{7}$$

The right-hand side of Eq. (7) is minimum for $\gamma = 0.87$, hence $L_{opt} = \gamma n$ with $\gamma = 0.87$. So, if we identify n_1 tags in the first subgroup in our FSAPB, $n = n_1$ is known, and then, the optimal frame size $L_{opt} = L_2$, for the next subgroup in our FSAPB can be decided by $L_2 = \gamma n_1$, and $L_k = \gamma n_{k-1}$ as in the previous section. One can compute the total number of time slots $T_{FSAPB,opt}(n)$ in the single optimal frame using

[1]Deriving the joint probability mass function of Y_i^r's is challenging due to the dependency among the random variables representing the number of tags that choose each slot. We approximate the expected value by assuming a large tag population and a binomial distribution.

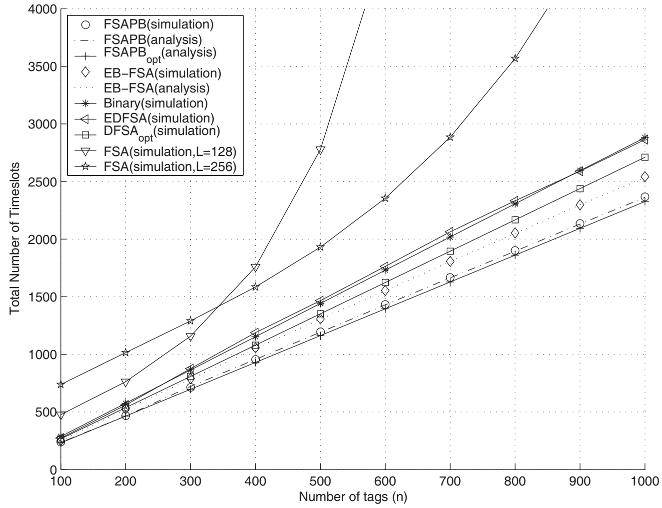

Fig. 2. Total number of time slots used to identify tags with the varying number of tags.

the binary tree protocol for collision resolution.

$$T_{FSAPB,opt}(n)=\sum_{r=0}^{n}\Big(E_r^n(L_{opt})\cdot(\alpha_r(2)+1)\Big). \qquad (8)$$

B. Proposed FSAPB

We have assumed that tags are uniformly distributed and the tags to respond to a reader is divided into M subgroups by bit masks. Let L_k and n_k be the frame size and the number of tags in the kth subgroup, respectively. In the first subgroup, L_p is used because the number of tags is not known a priori. If $\hat{P}_{coll}$ is less than P_{th}, additional slots L_{add} is used. This corresponds to the case that the binary tree protocol operates right after L_p when collisions occur during L_p. Then, the total number of time slots ${T_1}^l(n_1)$ is derived from Eq. (6) with $L = L_p$ and $n = n_1$,

$$T_1^l(n_1)=\sum_{r=0}^{n_1}\Big(E_r^{n_1}(L_p)\cdot(\alpha_r(2)+1)\Big). \qquad (9)$$

If $\hat{P}_{coll}$ is greater than P_{th}, additional slots L_{add} is not used, instead new frame L_1 is used. Let n_1' be the number of tags not successfully identified during L_p. Then, the total number of time slots ${T_1}^u(n_1)$ is

$$T_1^u(n_1)= L_p+\sum_{r=0}^{n_1'}\Big(E_r^{n_1'}(L_1)\cdot(\alpha_r(2)+1)\Big). \qquad (10)$$

One can assume $n_k = n_{k-1}$ due to the assumption of uniform distribution of tags by bit masks, and $L_k = \gamma n_{k-1}$. So the total number of time slots in the kth subgroup is

$$T_k(n_k)=\sum_{r=0}^{n_k}\Big(E_r^{n_k}(L_k)\cdot(\alpha_r(2)+1)\Big), \qquad 2\le k\le M. \quad (11)$$

Therefore, the total number of time slots $T_{FSAPB}(n)$ for the identification of all tags becomes

$$T_{FSAPB}(n) = T_1^u(n_1)I(\hat{P}_{coll} > P_{th}) + T_1^l(n_1)I(\hat{P}_{coll} \le P_{th}) + \sum_{k=2}^{M} T_k(n_k), \qquad (12)$$

where $I(\cdot)$ is an indicator function.

We evaluate the performance of optimal DFSA, binary tree protocol, optimal FSAPB and FSAPB. We set $L_p = 36$, $P_{th} = 0.6$, γ = 0.87 and $M = 4$. The number of simulation iterations is 10,000, and n is varied from 100 to 1000. In FSAPB_{opt} and DFSA_{opt}, we assume that the number of tags is known and the tag estimation is accurate. Owing to the assumption that the number of tags is known, FSAPB_{opt} needs not estimate the number of tags via grouping the tags into M subgroups. And FSA uses fixed frame size, 128 or 256. Fig. 2 shows the total average number of time slots for identification. We have verified the analysis by simulation. From the small gap between FSAPB and FSAPB_{opt}, we can deduce that pilot frame L_p for tag estimation is very efficient. Fig. 2 presents DFSA_{opt}, Enhanced DFSA (EDFSA) [3], binary tree, and EB-FSA which require more time slots by 14.56%, 21.01%, 21.77% and 7.44% than our FSAPB when n=1000.

IV. Conclusion

We have proposed fast tag estimation by a small pilot frame and binary tree-based collision resolution of RFID tags with a frame of each subgroup partitioned by bit masks. Our proposed FSAPB combines the advantages of DFSA which decreases the number of collided tags in a particular time slot, and of the binary tree protocol that has good performance when the number of tags is relatively small, which occurs due to grouping of tags into small subgroups via bit masks. FSAPB is observed to outperform the existing algorithms.

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