다중 패킷 수신을 이용한 RFID 충돌방지 알고리즘의 성능 향상

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Improving RFID Anti-Collision Algorithms with Multi-Packet Reception

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요 약

다수의 RFID 태그들로부터 발신된 메시지들 사이의 충돌을 빠르게 해소하는 일은 대규모 RFID 시스템의 성능을 결정짓는 중요한 문제이다. 본 논문에서는 충돌방지 (anti-collision) 알고리즘의 성능 향상을 위하여 다중 패킷 수신 (multi-packet reception) 기법을 사용할 것을 제안한다. 다중 패킷 수신 기법을 통해서 RFID 판독기는 동시에 전송된 다수의 태그를 충돌없이 수신 할 수 있다. 대표적인 충돌방지기법인 이진 트리 분리 (binary-tree-splitting) 알고리즘과 슬롯 알로하 (Slotted-Aloha) 알고리즘에 다중 패킷 수신 기법을 적용했을 경우의 성능향상을 분석하는 모델을 제안하고 제안된 분석모델의 정확성을 시뮬레이션을 통해서 비교 검증한다. 다중 패킷 수신 기법 적용시 큰 폭의 성능향상이 있음을 보이고, 다중 패킷 수신 기법의 이득을 최대화 하기 위해서는 RFID 판독기 안테나 디자인과 수신 신호 분리 기술이 중요함을 보인다.

Key Words : Anti-collision, Rfid, Multi-packet Reception, Binary Tree Splitting, Slotted Aloha

ABSTRACT

One of the important performance issues in large-scale RFID systems is to resolve collisions among responses from RFID tags. Considering two de facto anti-collision solutions, namely the binary-tree splitting algorithm and the Slotted-Aloha algorithm, we propose to use multi-packet reception (MPR) capability to enhance the RFID tag reading rate (i.e., throughput). MPR allows an RFID reader to receive multiple responses transmitted by tags at the same time. We analyze the effect of MPR capability in the above anti-collision algorithms, which is also validated by simulation. The analysis and simulation results show that RFID reader antenna design and signal separation techniques play an important role in improving RFID system performance with MPR capability.

Ⅰ. Introduction

The Radio Frequency Identification (RFID) system is to identify and track objects by attaching a small RFID tag to the objects. Each RFID tag stores information about the object, such as its unique identification number. When these tags reside within a reader's radio field, they transmit

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this information to the reader: objects eventually become identified. However, RFID tags are limited in computational power, memory and communication bandwidth. This limitation has become a crucial issue when a large number of tags need to be identified simultaneously, thus leading to what is called an anti-collision problem. To tackle this problem, two anti-collision algorithms, the slotted Aloha (S-Aloha) algorithm [1] and the binary tree splitting algorithm [2], have been considered. Their tag reading rates, however, are not sufficiently fast enough to simultaneously recognize a large volume of tags especially in delay-sensitive applications. When the target application is delay-tolerant, the tag collisions in RFID systems can be resolved over time even when the tag-reading rate is slow. However, in many RFID applications, a large volume of tags need to be identified within a limited time. For example, the user of a RFID inventory system may want to know the list of all items in a warehouse immediately without delay.

Thus, we propose to incorporate multi-packet reception (MPR) capability into an RFID reader in order to enhance the RFID tag reading rate. Our major contribution includes the presented probabilistic model and the Markov chain model which enables the performance analysis of the binary tree splitting algorithm and the S-Aloha algorithm with MPR capability.

Traditionally, the medium access control (MAC) layer has been using simple collision models: packets transmitted at the same time are destroyed, and retransmissions are required. Recently, the advent of sophisticated signal processing has changed many of the underlying assumptions made by conventional MAC techniques. For example, the use of an array antenna enables multi-packet receptions, which allows the reception of multiple responses transmitted by tags at the same time [3]. We propose to equip an RFID reader with the array antenna and leverage its MPR capability. Ward and Compton [5,6] analyzed the throughput improvement of S-Aloha packet radio networks with adaptive array antenna models. In contrast to their infinite traffic assumption of general packet radio networks, an RFID system deals with a finite number of tags at a certain moment. Hence, a packet arrival rate of an RFID system depends on the number of remaining, unrecognized tags. It is not possible for an RFID system to use the Markov chain model of [5, 6] in which states reach an equilibrium. With these in mind, we analyze the throughput improvement of binary-tree-splitting and Slotted-Aloha of an RFID system with MPR capability, and validate the analysis by simulation.

Mutli-packet reception can also be achieved by code division multiple access (CDMA) scheme [11]. However, the collision probability due to a random selection of CDMA codes still bounds the number of tags successfully decoded at a reader. In addition, the MPR capability with array antenna systems is different from that of CDMA systems: the presented throughput analysis model in this paper considers the generalized MPR capability of array antenna systems.

Ⅱ. System Model

We consider a simple RFID communication system in which an RFID reader reads multiple tags in its vicinity. An RFID reader broadcasts request messages to the tags. Since only the reader transmits on the downlink, there is no contention on the downlink request message. Upon receiving the request, each tag 'selectively' sends (or holds) a response message, according to the anti-collision algorithm. For simplicity, we will describe the two anti-collision algorithms on a slot basis assuming equal length for collided, idle and successful slots. The number of tags in our model is assumed to be fixed during each runtime of the algorithm since our focus here is to reduce the number of slots required to identify all the tags in the target volume by using MPR.

We assume the reader is equipped with an array of multiple antenna elements. A general model of M responding tags and a reader with an array of K antenna elements is the multi-input

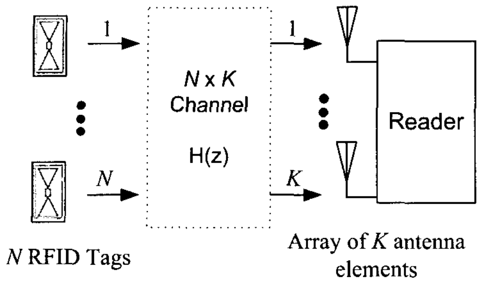

Fig. 1. RFID tag-to-reader MPR model

and multi-output (MIMO) channel as shown in Fig. 1. Although tags are separated and not antenna elements of one transmitter, M responding tags are synchronized in packet transmission because they transmit in response to the request message broadcast from the reader. This MIMO channel model of distributed transmitters is similar to the cooperative diversity channel model of [9,10] except that RFID tags do not relay messages of other tags in our model.

We use a simplified MPR model from [4]. The MPR capability of a reader is characterized by a pair of positive integers $\{F, K\}$ where $F \leq K$: F and K indicate *reception capability* and *collision-free capability*, respectively. Let i be the number of tags responding in a given slot. Besides the case of the idle slot (i = 0), three more cases are possible with an MPR model of $\{F, K\}$: 1) if $1 < i \leq F$, all i tags will be correctly recognized, 2) if $F < i \leq K$, only F tags among i tags will be successfully recognized, 3) when $i > K$, collision occurs and no signal can be decoded. If $i \leq K$, the reader is assumed to know the number of responding tags i possibly due to channel estimation and signal separation techniques (see the survey of papers in [7]). Authors of [5, 6] also provide exemplary channel estimation and signal separation techniques.

In general, a receiver MPR system cannot separate signals whose number is more than the number of antenna elements. Thus, K is optimistically assumed to be equal to the number of antenna elements, and F is bounded by K. The weakest MPR is the conventional collision channel $\{1, 1\}$, and the strongest MPR is $\{K, K\}$ ($K > 1$) that models perfect multi-packet reception. In between, F can take various numbers between 1 and K as a function of the channel conditions and signal separation algorithms. Here, we assume F is a constant while all the tags are read. This generalized model of various F makes the MPR model different from the adaptive array antenna models of [5, 6] and enable us to investigate on the performance improvement of the RFID system with various MPR capabilities.

Ⅲ. Binary Tree Splitting

3.1 Algorithm Description

A communication procedure between an RFID reader and RFID tags consists of a series of message triples (request, response, ACK), where each triple is completed in one slot. Each tag has a globally unique identifier (ID) represented by a string of bits. The reader specifies the range of tag IDs in the request message to which the tags falling under that range must respond. Upon correctly receiving responses, the reader acknowledges the recognized tags through the ACK message. The acknowledged tags hold their transmission of response message even though they fall in the ID range specified in the request message[1]. In the first slot, the reader requests all relevant tags in the reading volume to respond.

When a collision occurs (the number of responding tags is greater than K), say in the s-1th slot (or slot s-1), all tags involved in the collision are split into two subsets as illustrated in Fig. 2. The reader uses the successive bits of the original ID field to make a narrowed-down choice of the ID range.

In Fig. 2, for example, the range [00000,11111] (or xxxxx) will be split into two parts, 0xxxx and 1xxxx where x can be either 0 or 1. The reader requests *the first subset to respond in slot* s. Let i be the number of tags allotted to the first subset. If slot s is idle (i = 0), the second subset

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[1] This feature may be realized by the use of an "inventoried" flag such as the one employed at [1]

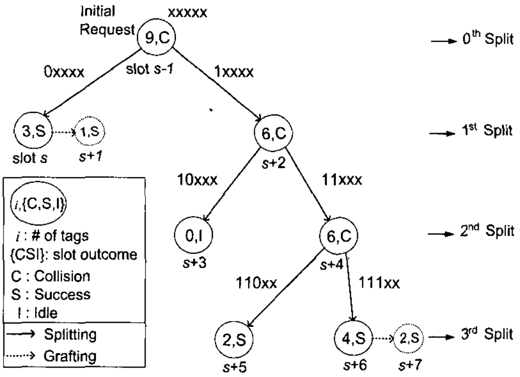

Fig. 2. Binary Tree Splitting Example (K=4, F=2)

is requested to respond in slot s+1 if slot s is successful $(0 < i \leq K)$, the reader reads all i tags using $\lceil i/F \rceil$ slots and the second subset is requested to respond in slot $s+\lceil i/F \rceil$. Particularly, if $F < i \leq K$, in addition to the first slot, $\lceil i/F \rceil - 1$ more slots are required to recognize all tags in a subset: we call these additional slots as "graft" slots. In the case of F=2 and i=3, for example, $\lceil 3/2 \rceil = 2$ slots are consumed with one graft slot and the second subset is examined starting from slot s+2 as shown in Fig. 2. If F=1, the reader reads all i tags in the first subset one by one by using i slots, and then, the second subset is asked to respond in slot s+i. On the other hand, if another collision occurs in slot s, i.e., $i > K$, the first subset splits again, while the second subset waits for the resolution of the first subset. This splitting mechanism is recursively iterated until no further collision occurs.

3.2. Throughput Evaluation

We evaluate the throughput (measured by the number of successfully recognized tags per slot) of the binary tree splitting algorithm. Let R be the number of bits indicating the initial ID range of interest, and $\rho = N/2^R$ be the tag density in the ID range of interest where N is the total number of tags to be read. Assume k be the number of bits mapped to K, $(K = 2^k)$. The probability that i tags fall in the range of the jth split, $P_i(j)$, and the probability of collision in that split, $P_{col}(j)$, are given by:

$$P_i(j) = \binom{2^j}{i}(1-\rho)^{2^j - i}\rho^i, \quad (0 \leq i \leq 2^j), \qquad (1)$$

$$P_{col}(j) = 1 - \sum_{i=0}^{K} P_i(j). \qquad (2)$$

Then, the expected number of slots in the jth split, $s(j)$ for $0 \leq j < R-k$, is expressed recursively as

$$s(j) = 1 + \sum_{i=F+1}^{K} \left\lceil \frac{i}{F} - 1 \right\rceil P_i(j) + 2 \cdot s(j+1) \cdot P_{col}(j),$$

with a boundary condition

$$s(R-k) = 1 + \sum_{i=F+1}^{K} \left\lceil \frac{i}{F} - 1 \right\rceil P_i(R-k). \qquad (3)$$

One slot is required by default, regardless of the possible outcomes: *Idle, Success, or Collision.*

Then, the expected number of slots to read all tags is $s(0)$ and the expected number of recognized tags per slot is given as $\frac{N}{s(0)}$.

Ⅳ. Slotted Aloha (S-Aloha)

4.1 Algorithm Description

The reader initiates the communication by sending a request message and then a series of message pairs follows. Each pair consists of simultaneous responses from tags and an ACK from the reader. We assume that each pair is completed in a slot. When the reader requests tags to respond, each tag holds the transmission of its data (ID) until expiration of a counter whose value is generated randomly and independently among tags. The reader announces the beginning of each slot by putting a gap pulse (e.g., no RF field for some designated time) at which the random number counter of each tag is decremented. When a collision occurs, each tag discovers the collision in the absence of an ACK message from the reader, and becomes backlogged. Each backlogged tag again waits for a random number of slots before retransmitting.

4.2 Throughput Evaluation

Let $P_{n,m}$ be the probability of having *n* tags $(0 \leq n \leq N)$ read successfully until the *m*th slot, where N is the total number of tags to be read. For purposes of analysis, we employ a two-dimensional Markov chain (n,m) where each of *n* and *m* corresponds to a dimension. At each state transition, *m* is always incremented by one, while the increment of *n* varies from zero to *F*.

If the initial transmissions (responses) from the tags and the retransmissions from backlogged tags are sufficiently randomized, it is plausible to approximate the total number of retransmissions and initial transmissions in a given slot as a Poisson random variable [8] with parameter $(N-n)\lambda$ as the total tag-responding rate, where λ is the response rate of a tag. Since the number of tags are finite, in other words, the tag-responding rate in a slot is determined by the number of unrecognized tags, $N-n$, multiplied by λ. The reader announces the value of λ in the request message.

Let $p(n,i)$ be the probability of *i* responding tags when *n* tags are already successfully recognized $(i \leq N-n)$:

$$p(n,i) = \frac{((N-n)\lambda)^i}{i} e^{-(N-n)\lambda} \tag{4}$$

Having *n* tags recognized, regardless of the slot number *m*, the probability of successful recognition in a slot, $P_s(n)$, is the summation of one-tag to *K*-tags responding probabilities. If the number of unrecognized remaining tags $N-n$ are less than *K*, the summation range will be one to $N-n$. Thus, $P_s(n)$ is given by

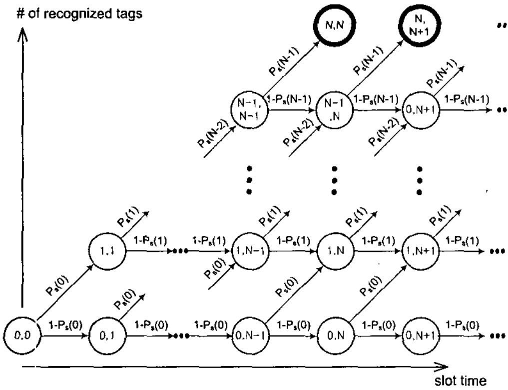

Fig. 3. Markov Chain for Slotted Aloha (F=1)

$$P_s(n) = \sum_{i=1}^{min(K,N-n)} p(n,i) \tag{5}$$

In the case of *F*=1, the state transition diagram is shown in Fig. 3. If the slot *m* is successful, the state (n,m) transits to $(n+1,m+1)$ (diagonal transition) with success probability $P_s(n)$; otherwise it transits to $(n+1,m+1)$ (horizontal transition) with probability $1-P_s(n)$. In S-Aloha, two outcomes of a slot, idle and collision, result in the same horizontal state transition. The state transition continues until all *N* tags are read, i.e., until one of the states (N,m') is reached, where $m' \geq N$.

In the general case of $F \geq 1$, state (n,m) can transit to $(n+i,m)$ where $1 \leq i \leq F$, since the MPR system is able to recognize up to *F* tags simultaneously. Then, we can define $P_{n,m}$ iteratively from the initial state $(0,0)$ by enumerating the possible ways that each transition may occur.

- $n=0, m=0$: the initial state

$$P_{0,0} = 1 \tag{6}$$

- $n > mF$ or $n > N$: Not possible, since at most mF tags can be read until *m*th slot and *n* is limited by the total number of tags *N*.

$$P_{n,m} = 0 \tag{7}$$

- $n=0, m \geq 1$: No tags has been read. The previous slot's outcome was idle (no tags) or collision. Only horizontal transitions have occurred from the initial state.

$$P_{n,m} = P_{n,m-1}(1-P_s(n)) \tag{8}$$

- $(m-1)F < n \leq min(mF,N)$: Have no horizontal transition from idle or collided previous slot but diagonal transitions from successful previous slots. In the Markov chain of Fig. 3, the leftmost states of each row correspond to this case.

$$P_{n,m}=\begin{cases} A & n<F \\ A'+B & n\geq F \end{cases} \tag{9}$$

$$A=\sum_{i=1}^{n}P_{n-i,m-1}\cdot p(n-i,i)$$

$$A'=\sum_{i=1}^{F}P_{n-i,m-1}\cdot p(n-i,i)$$

$$B=\sum_{i=F+1}^{\min(K,N-(n-F))}P_{n-F,m-1}\cdot p(n-F,i)$$

Both A and A' represents the transitions (cases) when all transmitting tags are successfully recognized because the number of transmitting tags, i, is F or less. B represents the transition from state $(n-F,m-1)$ to (n,m) when only F tags are recognized among i transmitted tags $(F+1\leq i\leq K)$. If the number of unrecognized tags $N-(n-F)$ are less than K, the summation range will be $F+1$ to $N-(n-F)$.

- $0<n<\min((m-1)F+1,N)$: Have both diagonal (*A*,*B*) and horizontal transitions (*C*).

$$P_{n,m}=\begin{cases} A+C & n<F \\ A'+B+C & n\geq F \end{cases} \tag{10}$$

$$C=P_{n,m-1}\cdot(1-P_s(n))$$

Then, the expected number of slots to read all *N* tags is calculated as

$$\sum_{m=\lceil N/F\rceil}^{\infty}m\cdot P_{N,m} \tag{11}$$

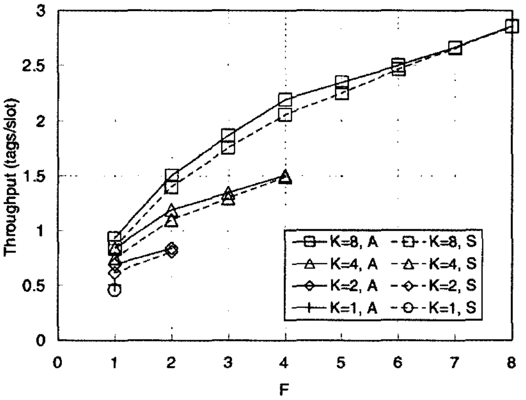

Fig. 4. Throughput of Binary Tree (R=12, ρ=0.5)

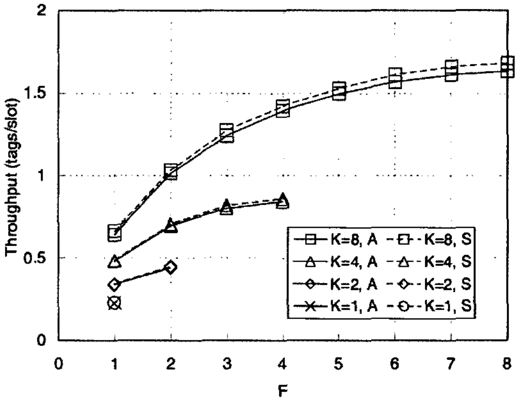

Fig. 5. Throughput of S-Aloha (optimal λ and N=150)

V. Numerical Results

Figs. 4 and 5 show the throughput of binary-tree-splitting algorithm and S-Aloha with various F, K combination. Throughput is plotted in terms of F. Each plot has a legend: the value of K and a character indicating analysis (A) or simulation (S). Note that K = 1 indicates the baseline case without MPR capability. First, in both graphs, the throughput of the proposed analytical model is almost equal with that of simulation results. Second, observing both graphs, increasing K alone can enhance the throughput even with small F; however, F plays a critical role to improve the throughput as K increases. In other words, both *reception capability* F and *collision-free capability* K must be large in order to achieve high throughput. The throughput with (2,4) MPR capability is higher than that with (1,8) MPR capability. Therefore, channel estimation and signal separation techniques (which determine the F) play an important role in improving RFID system performance as much as the number of receiving antennas (K) does.

When the throughput of binary tree splitting is analyzed and simulated in Fig. 4, R is set to 12 and the tag density ρ is set to 0.5, in order to consider large RFID systems. If we change the parameters R and ρ, the shape of plots may slightly change, but we have observed that the overall tendencies mentioned in the previous paragraph do not change. In Fig. 4, the throughput of S-Aloha is maximized over the tag response rate λ.

Although the overall tendencies of S-Aloha throughput still remain with different λ values, λ is controllable parameter and must be controlled on-line during a tag-reading process. In our experiments, for simplicity, λ is set at the beginning and fixed as a constant while all tag are read.

Ⅵ. Conclusion

This paper proposes how to leverage the physical layer MPR capability so that an RFID system achieves high throughput. By analysis and simulation, we show that both *reception capability F* and *collision-free capability K* must be large in order to achieve high throughput. Thus, the importance of channel estimation and signal separation techniques is emphasized as well as the importance of antenna design.

Future work will concentrate on how to set an optimal tag response rate λ considering MPR capability. Another future work is considering noise effect on binary-tree-splitting. In order to take a full advantage from MPR capability, binary-tree-splitting has to correctly distinguish the collision slot; it's difficult for RFID reader system to distinguish between collision and noise.

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