A Scheme to Increase Throughput in Framed-ALOHA-Based RFID Systems with Capture

Sung Youl Oh, Sung Hwan Jung, Jung Wan Hong, and Chang Hoon Lie

ABSTRACT—In this paper, a scheme to increase the throughput of RFID systems is presented, which considers the capture effect in the context of framed ALOHA protocol. Under the capture model in which the probability of one tag is identified successfully depending on the number of tags involved in the collision, two probabilistic methods for estimating the unknown number of tags are proposed. The first method is the maximum likelihood estimation method, and the second method is an approximate algorithm for reducing the computational time. The optimal frame size condition to maximize the system throughput by considering the capture effect is also presented.

Keywords—Tag collision, RFID, framed ALOHA, capture.

I. Introduction

Framed ALOHA is a discretized version of the ALOHA protocol which is a contention-based multiple access scheme. Every terminal in the transmission range randomly selects one of the time slots of a frame and transmits a packet upon receiving the base station's invitation command, which includes the frame size as an argument [1]. If two or more terminals transmit at the same time slot, a collision occurs and the received signal is garbled without capture. For RFID systems, the framed ALOHA modeling method is justifiable since the framed ALOHA approach has already been adopted as an option for the passive tag standard [8]. An interrogator commands tags to load a random number into their slot counter, which is a part of the non-volatile internal memory, and to decrement the value of the slot counter until it reaches zero, at which time, the tag replies.

The performance of a framed ALOHA system depends on the accuracy of estimating the unknown number of tags based on feedback from the reader and choosing the corresponding frame size. For passive RFID systems, [2] proposed a Markovian estimation scheme excluding the capture effect in a static environment, where the reader and the tags are fixed, whereas [3] suggested a Bayesian estimation approach. Both schemes gave good results under non-capture or perfect capture environments.

The capture effect refers to the successful receipt of a tag reply despite the presence of other tag replies transmitted simultaneously. A great deal of research has dealt with the capture effect, for example, considering fading models [4], [5] or delay capture [6]. In passive RFID systems, [3] proved the reliable existence of the capture effect even in a static environment. The capture effect would be more convincing in non-static cases of traveling tags or movable handheld readers. Although throughput improves with capture, the number of unknown tags tends to be underestimated. This results in improper frame size, which deteriorates the performance of the identification procedure.

In this paper, accommodating a general capture model, we present two probabilistic methods for estimating the unknown number of tags and the optimal frame size condition to maximize system throughput. We also compare performance results under delay capture relevant to passive RFID systems.

II. System Model

A capture probability of $Q(i)$ is specified, with which the reader will be captured by one of the tags whenever i tags transmit in a single slot. Then, $Q(i)$ only depends on the number of tags involved in a collision and strictly decreases as i

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increases as shown in [4]-[6].

Let (e, s, g) denote the number of empty, successful, and garbled slots in a single frame with L slots and T tags. The state of the system is defined in a given frame as $\mathbf{n}=(n(1),n(2),\cdots,n(T))$, where $n(i)$ represents the number of slots in each of which exactly i tags transmit. Let $m_n(i)$ be the number of slots which successfully decode the signal by the capture effect when $n(i)$ is given. Then, $m_n(i)$ is characterized by a binomial distribution denoted by $B(n(i), Q(i))$. Now, let $\mathbf{m_n}=(m_n(1),m_n(2),\cdots,m_n(T))$ be the vector representing the realization of the number of slots which succeed in their transmission considering the capture effect. There can be many possible realizations, $\mathbf{m_n}$ corresponding to one $\mathbf{n}$, and the following relationships are satisfied:

$$e=L-\sum_{i=1}^{T} n(i), \qquad s=\sum_{i=1}^{T} m_n(i), \\ g=\sum_{i=1}^{T}(n(i)-m_n(i)). \tag{1}$$

III. Estimation of Unknown Number of Tags

1. Maximum Likelihood Estimation (MLE)

The likelihood function (LF) of the unknown number of tags T under fixed frame size $L=e+s+g$ is

$$\mathrm{LF}(T;e,s,g)=\Pr(e,s,g\,|\,T)=\Pr(s,g\,|\,T). \tag{2}$$

Let $\Lambda=\{\mathbf{n}\,|\sum_{i=1}^{T} n(i)\le \mathrm{Min}(L,T)\wedge\sum_{i=1}^{T} i\cdot n(i)=T\}$ be the set of possible states when (e, s, g) is determined after the completion of one frame. $\Omega_{\mathbf{n}}=\{\mathbf{m_n}|\, s=\sum_{i=1}^{T} m_n(i)\wedge g=\sum_{i=1}^{T}(n(i)-m_n(i))\}$ represents the set of all possible vectors of $\mathbf{m_n}$ corresponding to a given $\mathbf{n}$. Then, (2) can be rewritten as

$$\begin{aligned}\mathrm{LF}(T;e,s,g)&=\sum_{\forall\mathbf{n}\in\Lambda}\Pr(s,g\,|\,\mathbf{n},T)\Pr(\mathbf{n}\,|\,T)\\ &=\sum_{\forall\mathbf{n}\in\Lambda}\sum_{\forall\mathbf{m_n}\in\Omega_{\mathbf{n}}}\Pr(\mathbf{m_n}\,|\,\mathbf{n},T)\Pr(\mathbf{n}\,|\,T).\end{aligned} \tag{3}$$

Here, $\Pr(\mathbf{n}\,|\,T)$ given in (14) of [7] and $\Pr(\mathbf{m_n}\,|\,\mathbf{n},T)$ can be given as

$$\Pr(\mathbf{n}\,|\,T)=(L!T!)/[L^T(L-s-g)!\prod_{j=1}^{T}(j!)^{n(j)}n(j)!], \tag{4}$$

$$\Pr(\mathbf{m_n}\,|\,\mathbf{n},T)=\prod_{n(i)>0}\binom{n(i)}{m_n(i)}Q(i)^{m_n(i)}(1-Q(i))^{n(i)-m_n(i)}. \tag{5}$$

Finally, the estimated number of tags T^*, which maximizes the likelihood function, can be obtained as

$$T^*=\mathrm{argmax}_T\ \mathrm{LF}(T;e,s,g). \tag{6}$$

2. Approximate Estimation (AE)

While the maximum likelihood estimation (MLE) method accurately estimates the unknown number of tags, the computational burden increases dramatically as T increases [7]. Therefore, an approximate estimation (AE) algorithm is proposed which can be easily incorporated into the existing tag identification schemes.

Let U be the number of tags that are not counted in the estimation, since they participated in successful slots where capture effects occurred. Then, the expectation of U given T and L can be calculated as

$$E[U\,|\,T,L]=\sum_{i=2}^{T}(i-1)E[n(i)]Q(i), \tag{7}$$

where

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

The proposed AE algorithm is given as follows:

Step 1. Get (e, s, g).

Step 2. Estimate $T^{(0)}$ using estimation method without capture:

$$T^{(1)}\leftarrow T^{(0)}+E[U\,|\,T^{(0)},L].$$

Step 3. Adjust: (e, s, g):

$$s\leftarrow s-\sum_{i=2}^{T^{(1)}}E[n(i)]\cdot Q(i),\ \ g\leftarrow g+\sum_{i=2}^{T^{(1)}}E[n(i)]\cdot Q(i).$$

Step 4. Estimate T^* using adjusted (e, s, g) and estimation method without capture.

After obtaining (e, s, g) from the reader, first estimate $T^{(0)}$ without considering the capture, and add the expected uncounted number of tags. Then, adjust (e, s, g) considering the estimated number of successful slots due to the capture effect. Estimation methods such as those in [2] or [3] can be adopted for estimation without capture.

IV. Optimal Frame Size under Capture Effect

In a capture environment, the expected throughput (measured in tags correctly received per slot) of one frame can be defined as

$$E[Th]=\frac{1}{L}\sum_{i=1}^{T}E[n(i)]Q(i), \tag{9}$$

where T can be estimated by MLE or AE methods, and $E[n(i)]$ is given by [10]. The optimal frame size can be obtained by finding the value of L that maximizes the expected throughput [11]. Under a specific capture environment, a matching table between the estimated number of tags and the optimal frame size suffices to control the system; hence, a practitioner does not need to calculate the optimal frame size in an online fashion. Moreover, since L is a natural number less than or equal to T, the optimal frame size can be calculated even by enumeration in the range of [1, T].

V. Numerical Example

The proposed schemes are evaluated using simulations for a fixed number of tags, while varying the frame size. We adopt the method of [3] as the estimation scheme without capture in the AE algorithm and the delay capture model under the frequency hopping spread spectrum [6]. The capture probability is determined by

$$Q(i) = q^i \ (i \geq 2). \quad (10)$$

Since transmission errors are not considered, $Q(1)$=1 and the parameter q can be determined by the physical time frame structure given a specific RFID system. Applying (10) to (9), the expected throughput reduces to

$$E[Th] = \left(1 + \frac{q}{L} - \frac{1}{L}\right)^T - \left(1 - \frac{1}{L}\right)^T + \frac{(1-q)T}{L}\left(1 - \frac{1}{L}\right)^{T-1}. \quad (11)$$

In Fig. 1, $E[Th]$ is shown with q=0.5. The two proposed schemes provide dependable estimates in all ranges of the traffic, while the estimation methods that do not consider capture show a tendency for substantial underestimation in high traffic cases (L=T/4 or L=T/2).

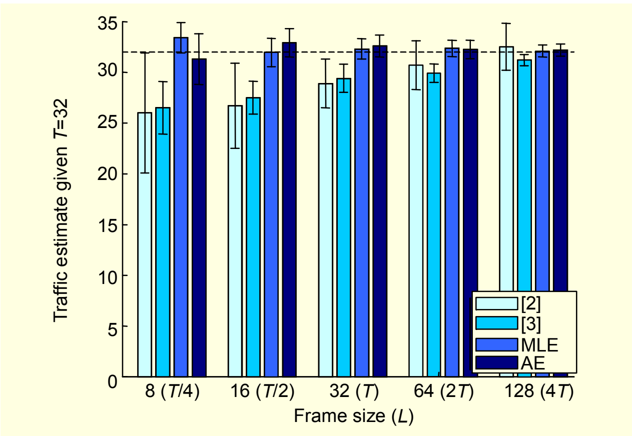

Fig. 1. Estimation accuracy with capture (q=0.5).

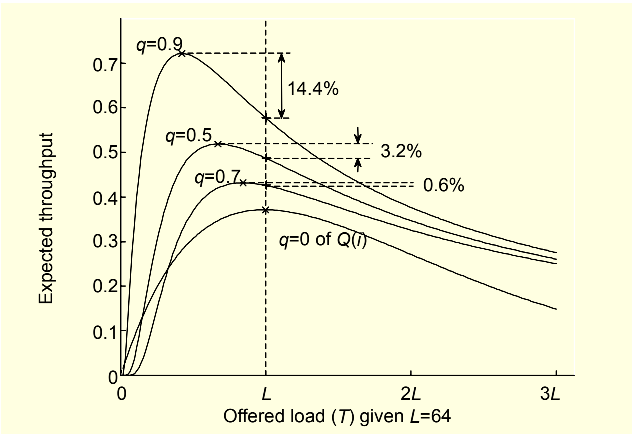

Fig. 2. Throughput improvement considering capture.

Figure 2 shows the expected throughput difference between cases in which the capture effect is either considered or not considered. In systems without capture, the optimal frame size is L, but with capture, it varies according to the capture environments. For example, the expected throughput improves by 14.4% at q=0.9 using the optimal frame size with capture.

VI. Conclusion

Considering the capture effect, two schemes to estimate the number of tags have been presented, as well as an optimal frame size condition which maximizes the throughput for the framed ALOHA-based RFID system. The two proposed methods can be incorporated into the existing estimation methods that have been developed for systems without capture. In any capture environment where the capture probability is determined by the number tags involved in a collision, the proposed methods, which consider capture, can make the identification procedure more efficient by providing a better estimate of the number of tags and by choosing a frame size which maximizes the expected throughput.

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