MAXIMUM A POSTERIORI APPROACH FOR ANONYMOUS RFID TAG CARDINALITY ESTIMATION

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ABSTRACT

Anonymous tag set cardinality estimation problem of Radio Frequency IDentification (RFID) using Maximum A Posteriori (MAP) approach is studied in this paper. The posterior probability of the total number of tags, given the frame size and the observed number of non-empty slots, is firstly determined. Then, the total number of tags is estimated to maximize the posterior probability. Computer simulation results demonstrate the effectiveness of the proposed approach.

***Index Terms*—** RFID, framed slotted ALOHA, anonymous estimation, MAP

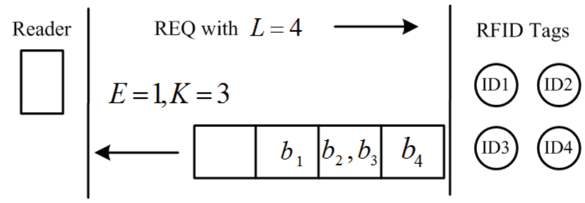

Fig. 1. ALOHA based protocol with the anonymous tag set cardinality estimation method

1. INTRODUCTION

Radio Frequency IDentification (RFID) technology has become very popular in many applications for identifying objects automatically [1]-[3]. The RFID reader normally transmits a request message consisting of a time slotted frame to all tags, and then each tag responds with its IDentity (ID) in a randomly selected slot [4], which is referred to as ALOHA based protocol [5]. One of the fundamental tasks in RFID systems is to estimate the total number of tags fast and reliably [4], which is required in various practical applications such as warehouse and supply chain management or intelligent transportation systems [6]. Usually, observations of the slots are used to estimate the total number of tags.

Due to privacy and security, the anonymous tag set cardinality estimation method has attracted much attention in recent works [7]-[10], where each tag responds to the reader's request with one bit or a sequence of bits, instead of its ID, which only allows the reader to detect if a slot is empty or non-empty. In order to estimate the tag set cardinality, M. Kodialam et.al., [7] propose the Zero Estimator (ZE) using the number of empty slots. However, when the total number of tags is increased, ZE is usually inaccurate because all the time slots might be non-empty. To overcome this issue, multiple readers with overlapping interrogation zones could be deployed, where the estimate of the tag set cardinality is determined using the estimated number of tags located in the interrogation zone of each reader [9], [10]. The disadvantages of the methods are high cost, system complexity and reader-to-reader interference [12]. Another solution is Probabilistic Zero Estimator (PZE) [7], [8] in which each tag is assumed to respond to the reader with a probability p. The optimal value of p is chosen to minimize the variance of the estimator. However, similar to ZE, PZE assumes the independence of the events of empty, singleton and collision among the slots, while the events are correlated. Therefore, there might be a room to improve the estimation accuracy.

In this paper, a Maximum A Posteriori (MAP) approach is proposed to deal with the anonymous tag set cardinality estimation problem with the ALOHA based protocol, in which the number of tags might be far greater than the frame size. The posterior probability of the total number of tags, given the frame size and the observed number of non-empty slots is first determined. Then, a search algorithm will be employed in order to find the tag set cardinality that maximizes the posterior probability. The performance of the proposed methods is evaluated with different system parameters and compared with that of conventional methods via computer simulations.

2. SYSTEM MODEL

The considered RFID system consists of a reader and n unknown tags in the communication range, where the ALOHA based protocol is used to obtain the information of the tag set cardinality. The reader first transmits a time slotted frame with size L to all tags, and then the tag t responds to the reader in a randomly selected slot with a bit $b_t = 1$. Thus, the reader only detects whether a slot is empty (slot without transmission) or non-empty (slot with transmission(s)). We denote E and K the numbers of observed empty and non-empty slots, respectively, and $L = E + K$. The anonymous scheme can be seen in Fig. 1, where the request with $L = 4$ is transmitted to all tags, and one empty (E=1) and three (K=3) non-empty slots are observed.

3. CONVENTIONAL METHODS

3.1. ZE Method

In order to estimate the total number of tags in the anonymous scheme, ZE [7] can be used by utilizing the observed number of empty slots. In particular, denoting p_E the probability that a slot is empty, we have

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

Then, the expected value of the number of empty slots $\bar{E}$ is given by

$$\bar{E} = Lp_E = L\left(1 - \frac{1}{L}\right)^n. \tag{2}$$

Hence, the estimate of n, which is denoted as $\hat{n}$, can be found by

$$\hat{n} = \frac{\log\left(\frac{E}{L}\right)}{\log\left(1 - \frac{1}{L}\right)}. \tag{3}$$

3.2. PZE Method

To cope with the problem where the number of tags is much greater than the frame size, PZE is proposed, in which each tag is assumed to respond with a probability p. Note that this assumption is valid only if tags are smart enough to implement the probabilistic transmissions as in [11], which is not available in usual RFID systems. $\bar{E}$, in this case, is expressed as

$$\bar{E} = L\left(1 - \frac{p}{L}\right)^n. \tag{4}$$

Then, the estimate of n can be determined as

$$\hat{n} = \frac{\log\left(\frac{E}{L}\right)}{\log\left(1 - \frac{p}{L}\right)}, \tag{5}$$

where the optimal p, which minimizes the variance of PZE estimator, is derived in [8] as $p = \min(1, 1.59L/n)$.

4. PROPOSED METHOD BASED ON MAP

Here, the MAP approach is considered to deal with the anonymous tag set cardinality estimation problem. In particular, we obtain the estimate $\hat{n}$ of the cardinality by maximizing the posterior probability of n given the observation of K non-empty slots and the frame size L ($K \le L$), denoted $P_L(n|K)$ as

$$\hat{n} = \arg\max_n P_L(n|K). \tag{6}$$

The probability $P_L(n|K)$ is obtained as

$$P_L(n|K) = \frac{\binom{L}{K} f(K, n)}{L^n}, \tag{7}$$

where $f(K, n)$ is the number of cases that n tags respond using K slots (none of the slots are empty). On the other hand, we denote by A_i ($i = 1, 2, ..., K$) a set of events that n tags respond within K slots but where the slot i among the K slots is always empty, and $|\mathrm{A}_i|$ the number of elements of A_i. Then, $f(K, n)$ can be written by

$$f(K, n) = K^n - |\mathrm{A}_1 \cup \mathrm{A}_2 \cup ... \cup \mathrm{A}_K|, \tag{8}$$

where $\mathrm{A}_i \cup \mathrm{A}_j$ is a union of A_i and A_j. Moreover, we have

$$\begin{aligned} |\mathrm{A}_1 \cup \mathrm{A}_2 \cup ... \cup \mathrm{A}_K| = & \sum_{1 \le i \le K} |\mathrm{A}_i| - \sum_{1 \le i_1, i_2 \le K} |\mathrm{A}_{i_1} \cap \mathrm{A}_{i_2}| + \cdots + \\ & + (-1)^{l-1} \sum_{1 \le i_1, i_2, ..., i_l \le K} |\mathrm{A}_{i_1} \cap \mathrm{A}_{i_2} \cap ... \cap \mathrm{A}_{i_l}| \\ & + \cdots + (-1)^{K-1} |\mathrm{A}_1 \cap \mathrm{A}_2 \cap ... \cap \mathrm{A}_K|, \end{aligned} \tag{9}$$

where $\mathrm{A}_i \cap \mathrm{A}_j$ is the intersection of A_i and A_j. We can see that $|\mathrm{A}_{i_1} \cap \mathrm{A}_{i_2} \cap ... \cap \mathrm{A}_{i_l}|$ represents the number of cases that n tags respond using $K - l$ slots out of the K slots, which can be determined by

$$|\mathrm{A}_{i_1} \cap \mathrm{A}_{i_2} \cap ... \cap \mathrm{A}_{i_l}| = (K - l)^n. \tag{10}$$

Hence, (9) can be rewritten as

$$\begin{aligned} |\mathrm{A}_1 \cup \mathrm{A}_2 \cup ... \cup \mathrm{A}_K| = & \binom{K}{1}(K-1)^n - \binom{K}{2}(K-2)^n \\ & + \cdots + (-1)^{l-1}\binom{K}{l}(K-l)^n \\ & + \cdots + (-1)^{K-2}\binom{K}{K-1}1^n. \end{aligned} \tag{11}$$

By substituting into (8), $f(K, n)$ is obtained as

$$f(K, n) = \sum_{m=0}^{K-1} (-1)^m \binom{K}{m} (K - m)^n, 1 \le K \le n \tag{12}$$

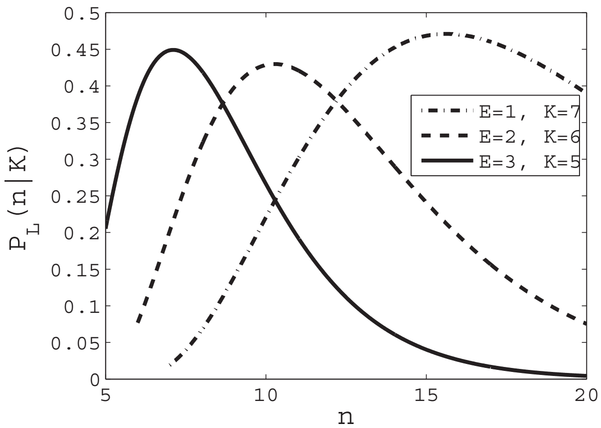

Fig. 2. $P_L(n|K)$
with $L = 8$

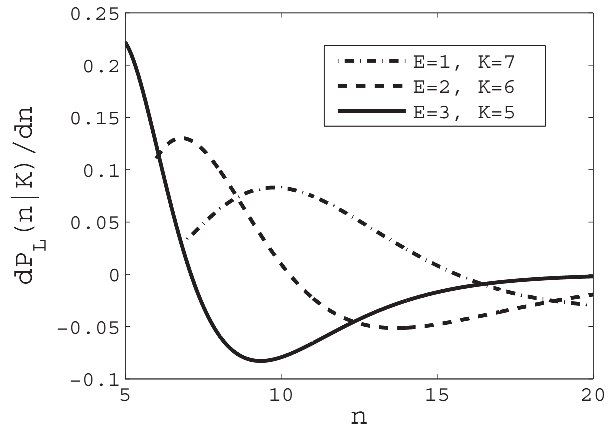

Fig. 3. $dP_L(n|K)/dn$
with $L = 8$

Thus, $P_L(n|K)$ is written as

$$P_L(n|K) = \frac{\binom{L}{K} f(K,n)}{L^n} = \frac{\binom{L}{K} \sum_{m=0}^{K-1} (-1)^m \binom{K}{m} (K-m)^n}{L^n}. \quad (13)$$

Assuming the continuous relaxation for n, the derivative of $P_L(n|K)$ with respect to n is given by

$$\frac{dP_L(n|K)}{dn} = \binom{L}{K} \sum_{m=0}^{K-1} (-1)^m \binom{K}{m} \left(\frac{K-m}{L}\right)^n \ln\left(\frac{K-m}{L}\right). \quad (14)$$

In order to see the behavior of $P_L(n|K)$, the existence and the uniqueness of the solution $dP_L(n|K)/dn = 0$ should be considered. Since closed form solutions are difficult to obtain, we employ the integer closest to the smallest solution of (14) obtained by numerical evaluation. Note that, the estimated total number of tags is greater than or equal to the number of non-empty slots i.e., $\hat{n} \geq K$. Also, the proposed method can be applied to the case with the probability p described in PZE by just dividing the obtained cardinality by p.

5. NUMERICAL RESULTS

In this section, the performance of the proposed method under different system parameters is evaluated via computer simulations, and compared with that of conventional methods. The simulation results are obtained by Monte Carlo method with $R = 10000$ runs.

We first plot the function $P_L(n|K)$ and its derivative $dP_L(n|K)/dn$ for three given simulation runs in Figs. 2 and 3 respectively, where the frame size is set to 8, and the observed numbers of empty slots are 1, 2 and 3. Note that, the value of n at the left most point of each line corresponds to the number of non-empty slots. We can observe that the equation $dP_L(n|K)/dn = 0$ has a unique solution, and the estimate of n should be the integer closest to the solution.

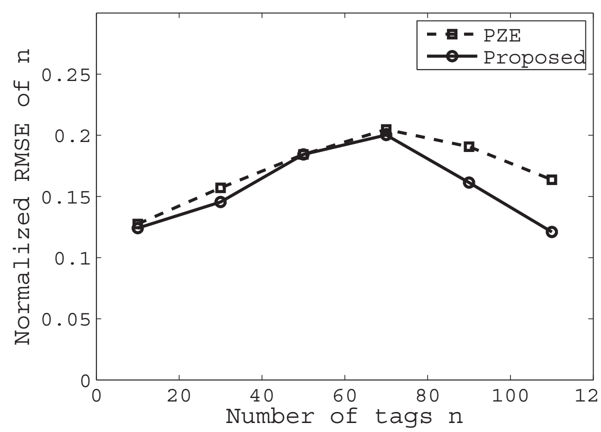

Fig. 4. Normalized RMSE of n with $L = 32$

In Figs. 4 and 5, we show the normalized Root Mean-Square Error (RMSE) performance of the estimated tag set cardinality obtained by the proposed method and PZE using the optimal probability p for large ($L = 32$) and small ($L = 8$) values of L, respectively. Note that, if observed slots are all non-empty, the tags are requested to re-respond to the reader. The normalized RMSE is defined as

$$\text{Normalized RMSE} = \sqrt{\frac{1}{R}\sum_{i=1}^{R}\left(\frac{\hat{n}_i - n}{n}\right)^2}, \quad (15)$$

where $\hat{n}_i$ is the estimate of n at the $i-$ th simulation run. In both figures, we can see the performance gain obtained by the proposed method against PZE. This would be because the proposed method does not rely on the assumption of the inde-

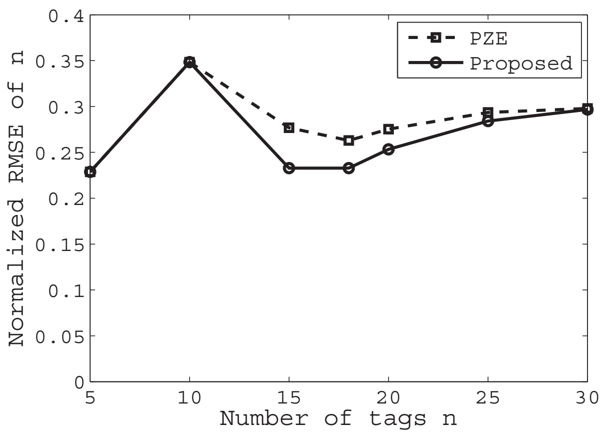

Fig. 5. Normalized RMSE of n with $L = 8$

pendence among the time slots.

6. CONCLUSION

In this paper, MAP approach has been considered, based on the observation of the number of non-empty slots, for the RFID anonymous tag set cardinality estimation problem with ALOHA-based protocol. Computer simulations are performed, which shows that the proposed approach gives better performance than the conventional PZE.

In the future work, we intend to apply the MAP approach for the tag set cardinality estimation problem in the onymous scheme where the reader can distinguish a slot to be either empty, singleton or in collision.

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