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Probabilistic Analysis and Correction of Chen's Tag Estimate Method

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***Abstract*—Radio frequency identification (RFID) is a ubiquitous wireless technology which allows objects to be identified automatically. An RFID tag is a small electronic device with an antenna and has a unique serial number. For some RFID applications and in the ALOHA-based anticollision algorithms, the number of tags in the system needs to be estimated. In Trans. Autom. Sci. Eng., vol 6, no. 1, pp. 9–15, Jan. 2009, Chen, a probabilistic method for tag estimation in ALOHA-based RFID systems was proposed, based on the maximum *a posteriori* probability. Although this approach is novel and useful, it has a mathematical error in modeling the problem. In this short paper, we address this problem and provide the correct probabilistic model for the ALOHA-based RFID systems. Some consequences of correcting the error in Trans. Autom. Sci. Eng., vol 6, no. 1, pp. 9–15, Jan. 2009, Chen, are discussed and the model is validated via simulation. Using the correct model, the performance of the ALOHA-based anticollision algorithm can be improved.**

***Note to Practitioners*—In an RFID system, packet collisions can occur when multiple tags transmit a reply message simultaneously in response to the query message from the reader. In this paper, we present an analytical model for frame slotted ALOHA-based anticollision protocol in RFID systems. Using this model, the optimal frame length, which results in the maximum channel efficiency, can be determined for ALOHA-based RFID systems. The EPCglobal standard has recommended using dynamic frame slotted ALOHA for RFID applications. Therefore, the proposed analytical model is useful for engineers and developers to implement dynamic frame length ALOHA algorithms for RFID systems. In addition to improving the channel efficiency, the proposed analytical model can be used for designing more reliable RFID systems from the privacy and security point-of-view.**

***Index Terms*—Framed ALOHA, radio frequency identification, tag estimate.**

I. Introduction

Radio frequency identification (RFID) is a ubiquitous wireless technology which allows objects to be identified automatically. An RFID system consists of readers and objects with tags. Each tag is a small electronic device with an antenna and has a unique serial identification (ID) number. An RFID tag transmits its ID (or sometimes only portion of its ID) over the wireless channel in response to an interrogation or query message by a reader [1]. Commercial applications of RFID include inventory checking, supply chain management, labeling products for rapid checkout at the counter and e-passport. In addition, there are many other potential applications such as smart refrigerators, which can recognize expired food items (e.g., milk containers with tags) [2].

RFID systems are prone to collisions due to the shared nature of the wireless channel used by the tags. To resolve this issue, different anticollision and tag singulation protocols have been proposed in the literature. These protocols can be classified into two categories: tree-based and ALOHA-based algorithms. Tree-based algorithms [4]–[8],

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such as the binary tree algorithm and the query tree algorithm, divide a set of tags into two subsets recursively until each subset has only one tag. In the ALOHA-based algorithms [9]–[19], such as dynamic frame slotted ALOHA and splitting frame slotted ALOHA, a frame is divided into a number of time slots and each tag chooses one of the time slots in response to the query message.

In some RFID applications and in dynamic frame slotted ALOHA algorithm, it is necessary to estimate the number of tags. In [3], Chen proposed a novel tag estimation algorithm for the ALOHA-based anticollision protocols. In this approach, the reader estimates the number of remaining tags in the RFID system after each interrogation based on *a posteriori* probability and uses this estimated number to determine the number of required time slots for the next interrogation. This approach can improve the performance of the ALOHA-based RFID anticollision algorithms. However, there exists an error in the probabilistic modeling of the problem. In this short paper, we present the correct probabilistic model for the ALOHA-based RFID systems, based on the initial assumptions made by Chen [3]. In other words, the main purpose of this paper is to "correct" the mistakes happened in [3], rather than providing an independent and new tag estimation method. The main contributions of this short paper are as follows.

- We first show that the probabilistic model proposed in [3] is incorrect. We then present the correct probabilistic model.
- The proposed model is validated via simulation. We compare the simulation results with the analytical results from [3] and our proposed model. The results from our analytical model closely match with the simulation results.
- Consequences of using the model suggested in [3] are shown and the required corrections are identified.

The rest of this paper is organized as follows. Section II summarizes the probabilistic model proposed in [3] and discusses about its problem. The correct probabilistic model for the ALOHA-based RFID systems is presented in Section III. Finally, some simulation results and corrections required for [3] is provided in Section IV.

II. Probabilistic Model Proposed by Chen

In this section, we summarize the probabilistic model proposed in [3]. In ALOHA-based RFID systems, the time frame is divided into time slots. Each tag chooses one of these time slots randomly and transmits its ID in the reply message. In each time slot, three events may happen. If only one tag chooses a specific time slot and transmits its ID, then the transmission is successful. This time slot is called a *single* time slot. If more than one tag choose a specific time slot, then packet collision will occur and the reader cannot decode the received signal. This is called a collided time slot. Finally, if no tag chooses a specific time slot, the reader will observe an empty time slot. If the reader chooses the number of slots in a frame to be much higher than the number of tags, then the channel capacity is wasted and the reader will observe multiple empty time slots. On the other hand, if the reader chooses the frame size to be much lower than the number of tags, then the chance of collision will increase. It has been proved that for optimal performance, the number of time slots in a frame is equal to the number of tags in the system [3].

A probabilistic model for ALOHA-based RFID systems was proposed in [3]. In that model, the reader first chooses a predefined number of time slots (128) to be the frame size. It then transmits a query message. Each tag randomly chooses a time slot and sends its reply in that time slot. After the first interrogation, the reader estimates the number of tags $\hat{n}$ in the system, based on the *maximum a posteriori probability* obtained from the number of empty (E), single (S) and collided (C) time slots. Then, the reader selects the frame size to be equal to ($\hat{n} - S$) and proceeds with the next interrogation. At the end of each interrogation, the values of $\hat{n}$, E, S and C are being updated. This procedure continues until all the tags have been identified in the system. In each interrogation, the summation of E, S and C is equal to L, which is the total number of time slots in the frame.

In [3], Chen suggested to calculate the probability of observing E empty, S single and C collided time slots, $P(E,S,C)$, and then find the $\hat{n}$ which maximizes this probability for each interrogation. He mentioned that in an RFID system containing n tags, the number of tags allocated in a time slot is a binomial distribution with n Bernoulli experiments and $1/L$ as the occupied probability. The probability of finding r tags in a time slot is given by [3]

$$B(r) = \binom{n}{r}\left(\frac{1}{L}\right)^{r}\left(1-\frac{1}{L}\right)^{n-r}, \quad 0 \leq r \leq n. \tag{1}$$

The probability of observing an empty slot, a single slot, and a collided slot can be obtained, respectively, as [3]

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

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

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

In the next step, the probability of observing E empty, S single, and C collided time slots, $P(E,S,C)$, was derived. In [3], the problem was modeled as a multinomial distribution with L repeated *independent* trials (choosing a time slot by a tag), where each trial can result in an empty, single, or collision event. However, *these events are not independent*, that is, the probability of observing E empty time slots affects the probability of observing S single time slots, and these two probabilities affect the probability of observing C collisions. However, based on the wrong assumption mentioned, $P(E,S,C)$ was calculated in [3] as

$$P(E,S,C) = \frac{L!}{E!S!C!}\left[\left(1-\frac{1}{L}\right)^{n}\right]^{E}\left[\frac{n}{L}\left(1-\frac{1}{L}\right)^{n-1}\right]^{S} \times\left[1-\left(1-\frac{1}{L}\right)^{n}-\frac{n}{L}\left(1-\frac{1}{L}\right)^{n-1}\right]^{C}. \tag{5}$$

After finding $P(E,S,C)$, the algorithm finds $\hat{n}$ which maximizes $P(E,S,C)$. That is $\hat{n} = \arg\max_n P(E,S,C)$. This $\hat{n}$ is considered as the estimation of n, which is the number of tags remained in the system. The algorithm proposed in [3] is shown in Algorithm 1.

Algorithm 1 The anticollision algorithm used in **[3]**

$L := 128$
Initialize E, S and C ($C \neq 0$)
$counter := 0$
while $C \neq 0$
  Interrogate all tags
  $counter := counter + 1$
  update E, S and C
  $\hat{n} := \arg\max_n P(E,S,C)$
  $L := \hat{n} - S$
end while

Although the approach proposed in [3] is logical, the results are inaccurate due to the mentioned mistake in calculating $P(E,S,C)$. Based on the above, a correct probabilistic model for ALOHA-based RFID systems is needed. By using the correct model and the approach proposed in [3], the reader can estimate the number of tags in the system accurately and assign an appropriate number of time slots in the frame for the next interrogation.

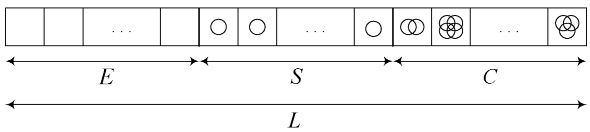

Fig. 1. The empty, single, and collided sections of a time frame in the analytical model.

III. Correct Probabilistic Model of the ALOHA Systems

As it was explained in Section II, the formulation proposed in [3] is incorrect because it is assumed that the events of observing empty, single, and collided time slots are independent from each other. This assumption is not valid and the mentioned events are dependent on each other. In this section, we present the correct derivation of the probability $P(E,S,C)$.

Here, we need to model our system mathematically and find the probability of observing a specific frame structure (E empty, S single, and C collided time slots). We consider a frame structure which has E empty slots in its first section, S single slots in the second section, and C collided slots in the last section, as it is depicted in Fig. 1. In this figure, each small circle in a time slot represents a single tag which has sent its ID in that time slot. Therefore, empty time slots are shown without any circle, single time slots are shown with one circle, and collided time slots are shown with multiple circles inside them.

In the model, the frame length is equal to L, while n represents the number of remaining RFID tags in the system. First, the probability of observing E empty slots in the first part of the frame is considered. This probability is denoted by $P_1(E)$ and is equal to

$$P_1(E) = \left(1 - \frac{E}{L}\right)^n, \qquad 0 \le E \le L. \tag{6}$$

In the next step, the probability of observing S single time slots in the second part of the frame conditioned to observing E empty slots in the previous step is considered. This probability is denoted by $P_2(S \mid E)$

$$\begin{aligned} P_2(S \mid E) = &\binom{n}{S}\left(\frac{S}{L-E}\right)^S\left(1-\frac{S}{L-E}\right)^{(n-S)} \\ &\times\left(\sum_{i=0}^{S}(-1)^i\binom{S}{i}\left(1-\frac{i}{S}\right)^S\right), \quad 0 \le S \le \min\{L-E, n\} \end{aligned} \tag{7}$$

where $(S/(L-E))^S$ is the probability that S tags are assigned to the first S slots among the total remaining $(L-E)$ slots, $(1-S/(L-E))^{(n-S)}$ shows the probability that the remaining $(n-S)$ tags are assigned to the remaining $(L-E-S)$ slots, and finally the summation $\sum_{i=0}^{S}(-1)^i\binom{S}{i}(1-i/S)^S$ is the probability that the mentioned S tags are assigned to S slots, *with no basket empty* , or in other words, each of the S slots only accommodates one and only one of the S tags (same as the classical urn model). The summation $\sum_{i=0}^{S}(-1)^i\binom{S}{i}(1-i/S)^S$ can be simplified as

$$\sum_{i=0}^{S}(-1)^i\binom{S}{i}\left(1-\frac{i}{S}\right)^S = \frac{S!}{S^S}. \tag{8}$$

Based on the above, $P_2(S \mid E)$ can be written as

$$\begin{aligned} P_2(S \mid E) &= \binom{n}{S}\left(\frac{S}{L-E}\right)^S\left(1-\frac{S}{L-E}\right)^{(n-S)}\frac{S!}{S^S} \\ &= \binom{n}{S}\left(\frac{(L-E-S)^{(n-S)}}{(L-E)^n}\right)S!. \end{aligned} \tag{9}$$

Now, we need to calculate the probability of observing C collisions in the last section of the frame conditioned to observing E empty and S single time slots in the previous steps. For $P_3(C \mid E,S)$, it is not that simple to calculate the probability of observing C collisions conditioned to E and S directly. Therefore, we define a class of acceptable events that represents different ways in which we can distribute $(n-S)$ tags in C slots in a way such that each slot contains *at least* two tags. We define the number of these acceptable events as $g_{n-S}(C,2)$. We have

$$P_3(C \mid E,S) = \frac{g_{n-S}(C,2)}{C^{(n-S)}} \tag{10}$$

in which $C^{(n-S)}$ is the total number of ways which we can assign $(n-S)$ tags to the remaining C time slots. Now, the main problem is to determine $g_{n-S}(C,2)$. Riordan [20] suggested and proved two closed form expressions for $g_\alpha(m,s)$ using the classical urn model in which α, m, and s denote the number of balls, the number of urns, and the minimum number of balls in each urn, respectively. The first closed-form expression for $g_\alpha(m,s)$ is

$$g_\alpha(m,s) = m g_{\alpha-1}(m,s) + m\binom{\alpha-1}{s-1}g_{\alpha-s}(m-1,s) \tag{11}$$

and the second one is

$$\begin{aligned} g_\alpha(m,s) = \sum_{k=0}^{m}(-1)^k\binom{m}{k}&\frac{\alpha!}{(s-1)!^k(\alpha-sk+k)!} \\ &\times g_{\alpha-sk+k}(m-k,s-1). \end{aligned} \tag{12}$$

Using (11) and (12), we can find the exact number of acceptable events in (10) by replacing α with $(n-S)$, m with C, and s with 2 for our problem. The above recursive equations can be calculated in two different ways. In the first approach, we can only use (11) and combine it with three simple logical constraints, as stated below:

a) **if** $(\alpha \neq 0)$ **and** $(m = 0)$, **then** $g_\alpha(m,s) = 0$;
b) **if** $(\alpha < ms)$, **then** $g_\alpha(m,s) = 0$;
c) **if** $(m = 1)$ **and** $(\alpha \neq 0)$ **and** $(\alpha \ge ms)$, **then** $g_\alpha(m,s) = 1$.

Using this method, we can start from an initial point and find the exact value for $g_\alpha(m,s)$ recursively. As the second approach, we can simplify (12) by replacing s with 2 and write

$$g_\alpha(m,2) = \sum_{k=0}^{m}(-1)^k\binom{m}{k}\frac{\alpha!}{(\alpha-k)!}g_{\alpha-k}(m-k,1) \tag{13}$$

in which

$$g_{\alpha-k}(m-k,1) = p_0(\alpha-k,m-k)\,(m-k)^{(\alpha-k)} \tag{14}$$

and $p_0(\alpha-k,m-k)$ is the probability that we have $(\alpha-k)$ tags and $(m-k)$ time slots and all the slots contain at least one tag. From [21], we have the mathematical expression for $p_0(\alpha-k,m-k)$ as

$$p_0(\alpha-k,m-k) = \sum_{v=0}^{m-k}(-1)^v\binom{m-k}{v}\left(1-\frac{v}{m-k}\right)^{(\alpha-k)}. \tag{15}$$

By substituting (14) and (15) into (13), we have

$$\begin{aligned} g_\alpha(m,2) = &\sum_{k=0}^{m}\sum_{v=0}^{m-k}(-1)^{(k+v)}\binom{m}{k}\binom{m-k}{v} \\ &\times\frac{\alpha!}{(\alpha-k)!}(m-k-v)^{(\alpha-k)}. \end{aligned} \tag{16}$$

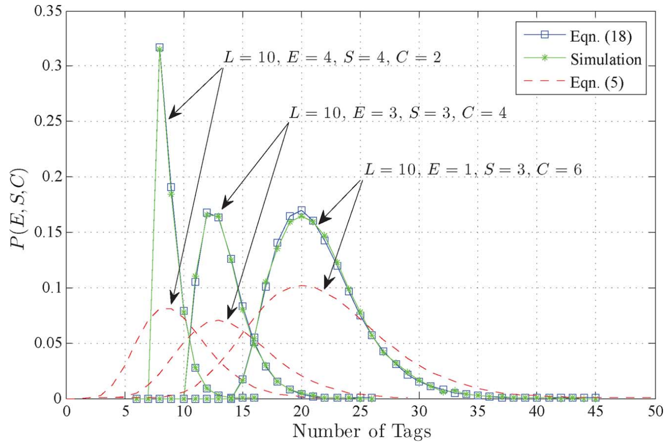

Fig. 2. *A posteriori* probability distributions using (5) from [3], (18), and the actual probabilities for a simulated RFID system.

Based on the above, (10) can be written as

$$P_3(C \mid E, S) = \sum_{k=0}^{C} \sum_{v=0}^{C-k} (-1)^{(k+v)} \binom{C}{k} \binom{C-k}{v} \times \frac{(n-S)!}{(n-S-k)!} \frac{(C-k-v)^{(n-S-k)}}{C^{(n-S)}}. \quad (17)$$

Using (6), (9), (10) and (16) or (11), we can determine $P(E, S, C)$, which is the probability of observing E empty, S single, and C collided slots as

$$P(E, S, C) = \left(\frac{L!}{E!\, S!\, C!} \right) P_1(E)\, P_2(S \mid E)\, P_3(C \mid E, S). \quad (18)$$

In (18), $(L!/E!\, S!\, C!)$ is the number of ways that the three mentioned sections in Fig. 1 can be scrambled and mixed with each other and make a random structure of E empty, S single, and C collided time slots. As it can be observed from (18), the probability $P(E, S, C)$ is a product of three other probabilities which are dependent to each other. The correct formula for calculating $P(E, S, C)$ is (18) which is different from (5).

It should be mentioned that the work by Floerkemeier previously stated the events of observing empty, single and collided time slots are dependent on each other in ALOHA-based RFID systems. He also suggested the "exponential generating function" technique to find the conditional probabilities of observing empty, single and collided slots [18]. In this note, however, we used a different method and found the closed-form formulation of $P_1(E)$, $P_2(S|E)$, $P_3(C|E, S)$, and $P(E, S, C)$.

IV. Simulation Results and Conclusion

In this section, we show that (5) is not confirmed by simulations while (18) agrees with the simulation results. Based on the new formulation, some of the figures in [3] need to be changed. These corrections are also provided in this section.

Fig. 2 shows the probability $P(E, S, C)$ obtained using (5) which was proposed in [3], the correct formula shown in (18), and the actual probability obtained via simulation. For the simulation, we used MATLAB and obtained the probability $P(E, S, C)$, using 10 000 iterations. The probabilities are plotted for three cases, ($L = 10$, $E = 4$, $S = 4$, $C = 2$), ($L = 10$, $E = 3$, $S = 3$, $C = 4$) and ($L = 10$, $E = 1$, $S = 3$, $C = 6$). The probabilities obtained via simulation are then compared with the probabilities obtained from (5), as well as the probabilities obtained from (18). As it can be inferred from

TABLE I
Correct Values of the Estimated n (Number of Tags) for the Algorithm in [3] ($L = 10$)

		C									
		0	1	2	3	4	5	6	7	8	9
S	1	2	3	4	5	6	7	8	9	10	11
	2	4	5	6	7	8	9	10	11	12	-
	3	6	7	8	9	11	12	13	14	-	-
	4	9	10	11	12	14	15	16	-	-	-
	5	12	13	14	16	17	19	-	-	-	-
	6	15	17	18	20	21	-	-	-	-	-
	7	20	21	23	25	-	-	-	-	-	-
	8	26	28	30	-	-	-	-	-	-	-
	9	35	38	-	-	-	-	-	-	-	-
	10	50	-	-	-	-	-	-	-	-	-

Fig. 2, (5) does not match with the results obtained from simulating an RFID system. The peaks obtained from (5) are lower than the simulated system and at some points, these peaks occur with one unit shift to right on n axis comparing to the simulated system. On the other hand, the probabilities obtained from (18) match with the simulated system. The peaks of $P(E, S, C)$ happen with the same heights and without any shift comparing to the simulated system.

We can also conclude that (5) is incorrect from Fig. 2 without relying on the simulated RFID system. If we observe $P(E, S, C)$ plotted for ($L = 10$, $E = 4$, $S = 4$, $C = 2$) and obtained from (5) at point $n = 5$, we can notice a positive value which is logically impossible. This probability should be equal to 0 because it is not possible to observe $E = 4$, $S = 4$, and $C = 2$, while we have only $n = 5$ tags in the system. Logically, $P(E, S, C)$ should be equal to 0 for values of n less than 8.

As another correction, a table was presented in [3] which showed the estimated number of tags for an RFID system ([3, Table I]). In this table, the number of tags were estimated based on *a posteriori* probability scheme for different values of S and C. We checked the values obtained from (18) with the values obtained from (5). Although the heights of the peaks for (18) and (5) are different, the values of n at which the peaks happen are the same in some cases. However, in some other cases, the values of n at which the peaks happen are different for (18) and (5). The correct values of estimated n are presented in Table I. The numbers shown in red color are different from those calculated by Chen in [3], while the numbers in black color are the same for both (5) and (18) and therefore, they are the same as the values shown in [3]. Although (5) is incorrect, the channel usage efficiency which was defined in [3] and shown below

$$U = \frac{n}{L} \left(1 - \frac{1}{L}\right)^{n-1} \quad (19)$$

is correct. Based on that, [3, Fig. 3] is correct.

So far, we explained Chen's mistake in modeling the ALOHA-based RFID systems and derived the correct analytical model, based on the assumptions made in [3]. An ideal ALOHA-based RFID system has been modeled in [3], however, there exist some technical issues which could have been considered. For instance, Chen assumed that the length of the time slots are equal for E, S, and C slots in ALOHA-based RFID systems, while this may not be always true as explained in [15]. As another example, it has been assumed in [3] that the reader does not make any mistake in deciding whether a time slot is singly occupied or collided. However, this may not be always true because of some technical issues, and some of the time slots which are interpreted as singly occupied can actually be collided slots [22], [23]. Moreover, it has been assumed that if a tag transmits its data in a single slot, the reader will receive this data for sure. In other words, the probability of transmission error has been considered to be zero in the ideal studied model [3]. However, this may not be always the case for real RFID applications, considering the noise and the interference in wireless channels [23]. In [3], it has been assumed that the length of the frame (L) can be any integer from 1 to 128, however, many protocols have specific constraints on the length of the frame. For instance, the length of the frame in ISO18000 6-C standard should be an integer in the form of $L = 2^Q$, where Q accepts integer values between 0 and 15 [19], [24]. Finally, the field nulls effect and its role in losing the power of tags is another technical issue which can be considered in a nonideal ALOHA-based RFID system [25].

Apart from the above mentioned concerns, the work in [3] introduced a worthwhile and effective scheme for tag estimation and it outperformed some other algorithms in the field as it was shown in [3, Figs. 4–8]. This scheme relies on estimating the number of tags that maximize the probability of observing a combination of empty, single and collided slots by the reader. Although this estimation adds some computational costs to the system, it is performed in the reader (or database). Therefore, using the scheme proposed in [3] does not impose any additional computation to the tags, and this is a great advantage of Chen's scheme. Using (18), the estimate of n will be more accurate. The effect of using the new formulation can be considered as an improvement to Chen's tag estimate method without diminishing its value.

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