An Efficient RFID Tag Estimation Method Using Biased Chebyshev Inequality for Dynamic Frame Slotted ALOHA

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***Abstract*—Radio Frequency Identification (RFID) is a wireless technology allowing for the automatic identification of tags (transponders). For the efficient identification in case of large tag populations, the RFID reader has to precisely estimate the number of tags in the reading area. Inaccuracies in this estimation lead to significantly increased reading times. Therefore, this paper proposes a novel tag estimation technique called biased Chebyshev inequality tag estimation method. This new method improves the existing Chebyshev inequality method by using a collision coefficient. This collision coefficient is calculated numerically using a two dimensional curve fitting approach. The proposed estimation method is compared to two common tag estimation methods in RFID systems. Simulation results of the proposed algorithm show a reading time reduction for large populations of approx. 25%.**

I. Introduction

In the recent years, the number of applications that use Radio-Frequency Identification Systems (RFID) has increased, and the reading speed became one of the most critical issues in these applications. Such RFID networks consist of: 1) Readers (Interrogators), which are responsible of scanning the interrogation area and identifying the tags. 2) Tags (Transponders), which store the data to be read by the readers. In RFID systems, the tags typically share a common communications channel. Thus, there is a certain probability of tag-collisions, i.e. multiple tags answer simultaneously. This collision probability naturally increases in dense networks with many tags. Since passive tags are the most practical tags in the market, because of their low price and simple design, they cannot sense the channel or communicate with the other tags. A a result, the reader is responsible for coordinating the network and has to avoid tags collisions using specific anti-collision algorithms.

Previously published RFID literature divides RFID anti-collision algorithms into two main classes. These are the deterministic algorithms which are Tree based [1], [5], and the probabilistic algorithms which are ALOHA based [2], [3], [6], [9]. ALOHA based algorithms are the most commonly used algorithms in RFID standards due to their simplicity and robustness. Initially, the ALOHA algorithms have been developed for packet radio networks [4]. The main idea of ALOHA based protocols is that the nodes of the network transmit their packets randomly in time. In case of a collision, the responsible node retransmits the collided data again. The theoretical maximal reading efficiency of ALOHA is only 18%. This efficiency is doubled by dividing the time into fixed slots. Using such Slotted ALOHA, the nodes of the network are only allowed to transmit their packets during these slots. The main disadvantage of this protocol is its low reading efficiency under heavy traffic (dense network). To improve the reading efficiency the Frame Slotted ALOHA (FSA) [8] protocol is used. Here, the tags are allowed to choose one slot within a given number of slots arranged in a frame.

Based on Random Access Theory, for the number of tags n, the distribution of these tags in each frame length of L slots can be expressed as given in [7] by the following equation:

$$a_0 = L\left(1 - \frac{1}{L}\right)^n,\ a_1 = n\left(1 - \frac{1}{L}\right)^{n-1},\ a_k = L - a_0 - a_1 \quad (1)$$

where a_0, a_1, and a_k are respectively the number of idle (no tag responds), successful (one tag responds), and collided (multiple tags respond) slots per frame.

The main task is finding the frame length L that maximizes the number of successful slots w.r.t. the number of idle and collided slots. However, in practical applications, the number of tags n in the interrogation region is unknown. Furthermore, the number of tags may even vary, e.g. when the tags are mounted on moving goods. Therefore, Dynamic Framed Slotted ALOHA (DFSA) [7] is commonly used. DFSA first estimates the number of tags in the interrogation area, and then calculates the optimal frame size L for the next reading cycle. Multiple cycles are generally required, as the data in the collided slots has to be re-transmitted. Naturally, the number n of unread tags reduces from cycle to cycle.

Depending on previously published RFID work, the performance of the anti-collision algorithms mainly depends on the accuracy of the estimation of the number of tags n. If the number of estimated tags is significantly too low compared to the actual number of tags, the resulting frame length would lead to many collisions which reduces the performance. A similar effect results if the number of estimated tags is significantly too high. This would result in many idle slots, which also reduces the performance.

Classical estimation methods have been proposed by Vogt and Shoute. The lower bound estimation method proposed by Vogt [9] states that the remaining number of tags is double the number of collided slots in the previous frame. Schoute [7] proposed a posterior expected factor of 2.39 to estimate the number of tags in the interrogation area. This expected value is exact if and only if the the prior distribution of the tags is Poisson distribution. In [9], Vogt presented an anti-collision protocol using classical Chebyshev inequality estimation function. However this estimation method assumed unity coefficients for the estimation equation.

This paper proposes a new biased Chebyshev inequality tag estimation method. The overall reading time of the proposed anti-collision protocol is calculated and compared with the reading time using the classical Chebyshev inequality estimation method. In Section II, the proposed biased Chebyshev inequality estimation method is presented. In section III, a brief description of the performance analysis of DFSA, and the proposed biased Chebyshev inequality estimation method is applied on this anti-collision algorithm. Finally, section IV presents simulation results, before the paper concludes in section V.

II. New Biased Chebyshev Inequality Estimation Method

This section first introduces the classical Chebyshev inequality tag estimation method for RFID systems. Next, the proposed biased Chebyshev inequality tag estimation method is described. Then, the effect of the collision coefficient value for different parameter configurations is presented.

A. Classical Chebyshev Inequality Tag Estimation Method

The classical Chebyshev inequality tag estimation method is based on searching for the optimal value of the number of tags n that minimizes the distance between the read results c_k in the previous reading cycle and the expected values $a_k^{L,n}$ from equation 1. This estimation function is presented as:

$$\varepsilon_{conv}(L, c_{0,1,k}) = \min_{n} \left\{ \left|a_0^{L,n} - c_0\right| + \left|a_1^{L,n} - c_1\right| + \left|a_k^{L,n} - c_k\right| \right\} \tag{2}$$

Where c_0, c_1, and c_k are respectively the actual numbers of idle, successful, and collided slots in the previous reading cycle under frame length L. Moreover $a_x^{L,n}$ are the estimated numbers for a given n as shown in equation 1.

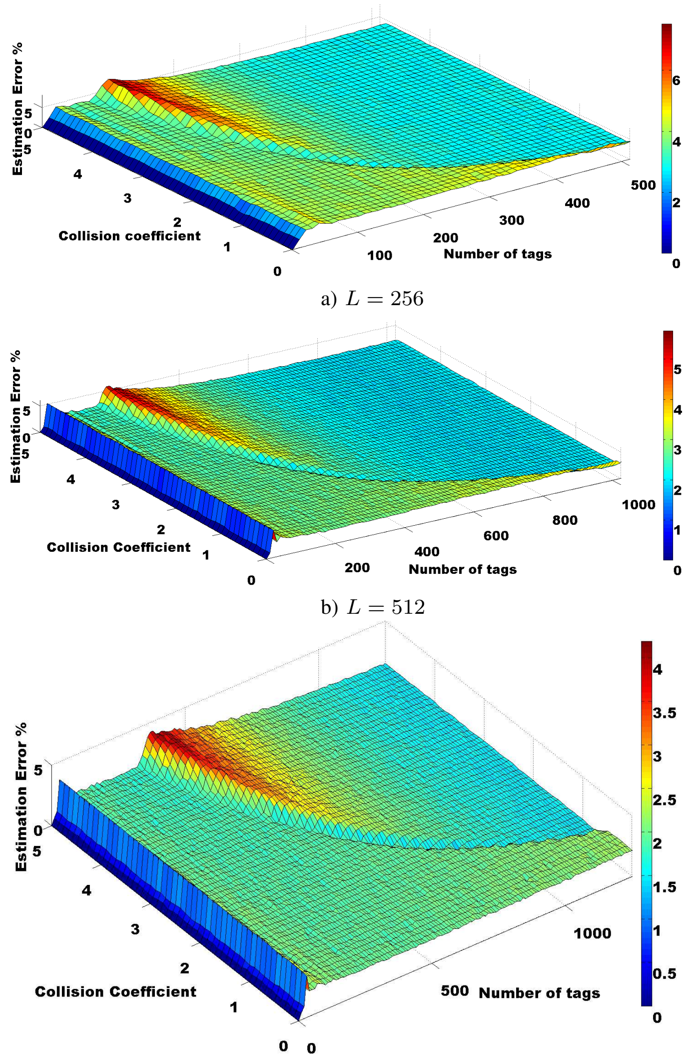
Equation 2 assumes identical weighting for the deltas between the read and estimated values for the number of idle, successful, and collided slots. However, this is not the optimal tag estimation method, because these deltas have different effects on the accuracy. Each successful slot represents only one tag, while the number of tags in a collided slot may be two or higher. As a result, a new biased factor for the collided slots is proposed that takes this effect into account.

B. Proposed Biased Chebyshev Inequality Tag Estimation Method

In this section, the proposed biased Chebyshev inequality tag estimation method is presented. The main idea of this method is similar to the classical Chebyshev inequality tag estimation method as shown in equation 2. However, a new collision coefficient γ_c is added that weights the number of collided slots. This leads to the equation:

$$\varepsilon_{new}(L, c_{0,1,k}) = \min_{n} \left\{ \left|a_0^{L,n} - c_0\right| + \left|a_1^{L,n} - c_1\right| + \gamma_c \left|a_k^{L,n} - c_k\right| \right\} \tag{3}$$

The proposed collision coefficient γ_c is a variable used to reduce the estimation error of the number of tags n. The optimal



a) $L = 256$

b) $L = 512$

c) $L = 1024$

Figure 1. Tag estimation error as a function of the collision coefficient γ_c, and the number of tags n for different frame lengths L

value of this coefficient depends on the number of the tags in the reading area and the frame length L. Numerical analysis as shown in figure 1 were used to find the optimal value for γ_c in different parameter configurations.

Figure 1 shows simulation results for the estimation error (in percent) as a function of the number of tags and the collision coefficient γ_c for different frame lengths L. According to the figure, the estimation error differs significantly with the collision coefficient. It is clear that the optimal value of the collision coefficient γ_c, which gives minimum error, is not always unity. The optimal collision coefficient γ_c is a function of the estimated number of tags n and the frame length L. Based on figure 1, the curve can be divided into three different regions:

- The first region is characterized by a low number of tags w.r.t. the frame length ($n \ll L$). In this case, the number of collided slots is almost zero. Thus, the proposed correlation coefficient has low effect.
- The second region is characterized by a high number of tags w.r.t. the frame length ($n \gg L$). In this case,

- the number of collided slots is very dominant. Thus, the proposed correlation coefficient has also low impact as the number of empty or successful slots in equation 3 is almost zero.
- The third region is the region of interest in practical applications where the frame length almost matches the number of tags ($n \simeq L$). In this region, the collision coefficient can be used to minimize the estimation error. As shown in figure 1, the optimal value is not always unity, and varies depending on the number of tags and the current frame length.

The task is finding a general formula for the collision coefficient γ_c that minimizes the estimation error in terms of the frame length L and the estimated number of tags n_{est}. The is achieved numerically using two dimensional curve fitting with 10.000 iterations for each parameter configuration. This method can be divided into two basic steps:

- The first step is finding the optimal collision coefficient γ_c as a function of the frame length L, which is the first dimension in the two dimensional curve fitting problem. The estimation error in the number of tags is calculated for different values of the collision coefficient under a constant number of tags and a specific frame length. This process is repeated for all possible values of the frame length. In each iteration, the value of the collision coefficient which results minimum error in tag estimation is calculated. After looping on the all possible values of frame lengths, there will be two vectors, one of them is the collision coefficient γ_c and the other is the corresponding frame length L under the specific estimated number of tags n_{est}. By using the first order curve fitting between these vectors, the relation between the optimal collision coefficient γ_c and the frame length L will be as shown in equation 4:

$$\gamma_c = f_1 \cdot L + f_2, \tag{4}$$

  where f_1 and f_2 varies with the estimated number of tags n_{est}.
- The second step is to loop over all possible values of the number of tags to have f_1 and f_2 as vectors. However, it is not practically to loop on all expected number of tags, as this is an infinite loop. Therefore, the proposed collision coefficient function is calculated under the condition in equation 5.

$$\frac{L}{2} < n < 2L \tag{5}$$

Then two first order curve fitting process would be done to get f_1 and f_2 as a function of the estimated number of tags n_{est}. Finally, the proposed final equation of the collision coefficient after the two dimensional curve fitting results in:

$$\gamma_c = (1.2 \times 10^{-4} n_{est} - 0.09) \cdot L + (0.0016 \times n_{est} + 8.36), \tag{6}$$

where i presents the reading cycle number.

III. Biased Chebyshev Estimation under the DFSA Anti-Collision Algorithm

In this section, a brief description about the DFSA anti-collision protocol is presented. After that, we show how we applied our proposed biased Chebyshev estimation method on DFSA anti-collision algorithm.

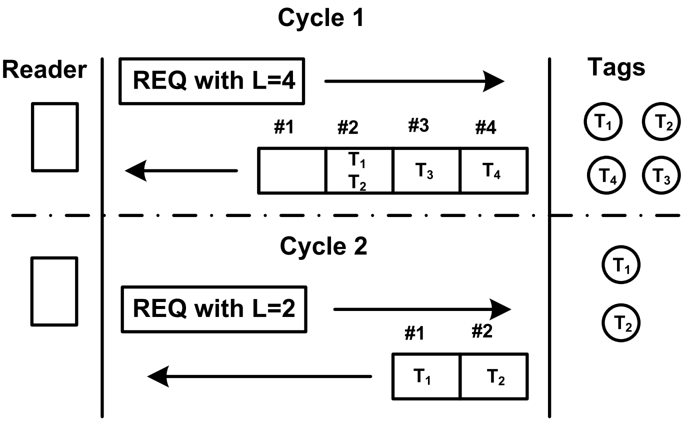


Figure 2. Anti-collision process with dynamic frame slotted ALOHA

The conventional definition of the DFSA reading efficiency η [7] is:

$$\eta = \frac{number\, of\, successful\, slots}{frame\, length}. \tag{7}$$

The main goal of DFSA algorithm is to estimate precisely the number of tags in the reading area, afterwords finding the optimal value of the frame L, which maximizes the reading efficiency η, based on the equations 1 and 7. This results in:

$$\eta = \frac{n}{L}\left(1 - \frac{1}{L}\right)^{n-1}. \tag{8}$$

As e.g. shown in [7], the reading efficiency η is maximized when $L = n$.

Figure 2 presents an example for the DFSA anti-collision process with $n = 4$ tags and a frame length of $L = 4$. According to the figure, the first slot in the first reading cycle is idle. A collision occurred within the second slot between tag_1 and tag_2. Furthermore, tag_3 and tag_4 are identified in slots 3, 4 respectively. Consequently, the two unidentified tags $tag_1$and tag_2 remain in the second reading cycle. For maximizing the reading efficiency, the frame size should be identical to the number of tags in the interrogation region. Therefore, the frame size in the second reading cycle has to equal 2. It is clear that the robustness of the estimation method is the most important part of the anti collision protocol, because if the anti-collision protocol has a big estimation error, the frame length will be set to a highly incorrect. This means that the protocol will work with a low reading efficiency. However, anti-collision protocols offering an accurate tag estimation method, will always work close the maximum reading efficiency.

In this part we will show how the results in the previous section can be applied on the DFSA algorithm, and how this affects the overall performance. Equation 6 presents the optimal value for the collision coefficient γ_c as a function of the number of tags n and the frame length L. The proposed anti-collision algorithm starts with the initialization of the parameters, which are the starting frame length and the initial expected number of tags in the reading region. After that, the algorithm observes the values of the number of idle, successful, and collided slots (c_0,

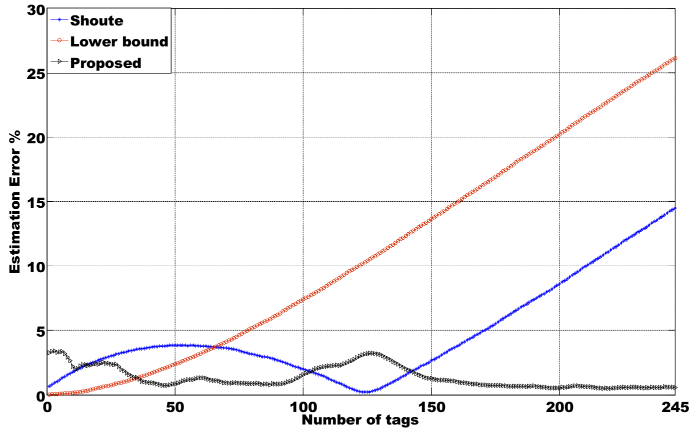


Figure 3. Tag estimation error for different estimation algorithms as a function of the number of tags n for a fixed frame length of $L = 128$

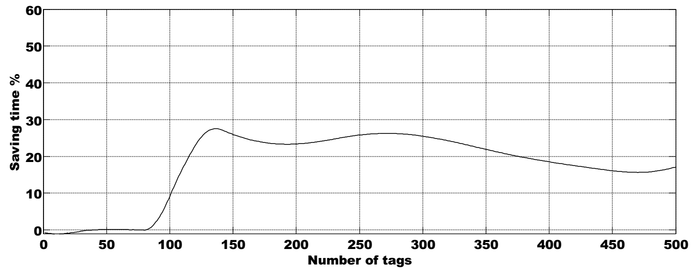


Figure 4. Saving of time using the proposed biased Chebyshev estimation w.r.t. the classical Chebyshev as a function of the number of tags n assuming a starting frame length of $L = 128$

c_1, and c_k). At this time the algorithm is able to calculate the new value of the collision coefficient γ_c^i for the current reading cycle using equation 6. Then the new estimated value of the number of tags is calculated using equation 3, and substituted in this equation by the updated value of the collision coefficient γ_c. This procedure is repeated until all slots of the current frame are empty slots.

The proposed biased Chebyshev anti-collision algorithm is summarized as follows:

Algorithm 1 Biased Chebyshev anti-collision algorithm

For each frame{
  initial parameters:
    $i = 1$ // frame counter
    $L^i = L_{ini}$ // initial frame length
    $n_{est}^i = n_{ini}$// initial estimated number of tags
  repeat:
    $i = i + 1$ // frame counter
    observe c_0, c_1, c_k //no. of slots
    γ_c^i= function of (L^i, n_{est}^{i-1}) // next collision coefficient
    calculate n_{est}^i // estimated number of tags
    $L^{i+1} = n_{est}^i$ //next optimal frame length
  until, $c_1 and\, c_k = 0$}

IV. Results and Performance Comparison

Figure 3 presents simulation results on the tag estimation error (in percent) for the proposed biased Chebyshev estimation method compared to the most common tag estimation methods in RFID systems, which are Schoute [7] and Lower bound [9]. The simulations in figure 3 use the frame length $L = 128$. According to the simulation results, the Lower bound estimation is the most accurate estimation method when the number of tags is small compared to the frame length, otherwise it is worse than our proposed algorithm. The Schoute estimation method is the most accurate algorithm when the number of tags in the reading area is almost equal to the frame size, otherwise it is worse than our proposed estimation algorithm. When the number of tags in the reading area is quite large w.r.t. the frame length, the proposed algorithms gives significantly improved results due to the effect of the proposed collision coefficient.

One could argue that the relatively small improvement of the estimation error has also low impact on the overall reading efficiency. Therefore, figure 4 shows the resulting saving time of our proposed algorithm compared to the classical Chebyshev algorithm. Here, a starting frame length of $L = 128$ in addition to 10.000 iterations have been used. In case of few tags, both algorithms obtain identical results as almost no collisions occur. However, when the number of tags reaches the frame length, the proposed algorithms shows its benefits. The overall time to read all tags in the interrogation area can be reduced by more than 25% compared to the classical algorithm.

V. Conclusions

This paper proposes a new tag estimation method for frame slotted ALOHA anti-collision algorithms for RFID systems. The proposed method collision coefficient weight in Chebyshev inequality tag estimation method. The reading time using the proposed tag estimation method is less than the reading time using the conventional one. This simulation results prove that it can decrease the reading time around 25% compared to the reading time using the conventional estimation method.

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