EURASIP Journal on Wireless Communications and Networking

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--Manuscript Draft--

Manuscript Number:	
Full Title:	Time Aware Closed Form Frame Slotted ALOHA Frame Length Optimization
Article Type:	Research
Section/Category:	Regular submission
Funding Information:	
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Time Aware Closed Form Frame Slotted ALOHA Frame Length Optimization

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***Abstract*—Calculating the optimal frame length for Frame Slotted ALOHA in RFID systems is a critical issue as it highly affects the reading efficiency, and hence the reading time. Most previous studies have focused mainly on the conventional definition of the reading efficiency, which is the ratio between the number of successful slots and the total number of slots (frame length). However, the duration of the slots in RFID systems depends on whether the slot is idle, successful, or collided. Some other state-of-the-art studies have focused on optimizing the frame length taking into consideration the differences in slot durations. However, they do not deliver a closed form solution for the optimum frame length in terms of the differences in slots durations. Therefore, this paper proposes a closed form solution for the optimum frame length for FSA by optimizing the "Time-Aware Framed Slotted ALOHA (TAFSA) efficiency", which considers the differences in the slot durations. Simulations indicate that the proposed solution gives the most accurate results with respect to the exact solution. Moreover a gain of approx. 10% in terms of reading time wrt. the classical algorithm using parameters of the ISO 18000-6C UHF-RFID standard. However, the results can also be applied to other systems based on Frame Slotted ALOHA.**

I. INTRODUCTION

Over the recent years, the number of applications that use Radio-Frequency Identification Systems (RFID) has increased, and their number is expected to further grow in the near future. One main application is the area of logistics, where e.g. hundreds of tags (transponders) may be closely placed on pallets. This naturally requires fast RFID readers (interrogators), in order to not slow down the delivery process of the actual goods. Commonly used RFID standards in the area of logistics (e.g. ISO 18000-6C [1]) base on TDMA (time division multiple access), which leads to a certain probability of tag-collisions on the communications channel. As the tags are of low price and simple design, they neither can sense the channel nor communicate with the others. Moreover, they are identified once during the reading process [1]. Hence, the readers are responsible for coordinating the network, and for the avoidance of collisions using anti-collision algorithms.

According to the previously published RFID work, Frame Slotted Aloha (FSA) [2] is the most widely used anti-collision protocol for RFID systems due to its simplicity and robustness. In FSA, the communication timing between the reader and the tags is divided into TDMA frames, each frame includes a specific number of slots. During the reading process, each active tag randomly assigns itself to one of the available slots in a frame. Therefore, each slot can take one of the three different states: 1) Successful Slot: Only one tag chooses this slot, is fully identified, and then deactivated by the reader within the following frames. 2) Collided Slot: Multiple tags reply, resulting in a collision. The collided tags normally remain in their active state and retry their transmission in the next frame. 3) Idle Slot: No tag responds and the slot remains unused.

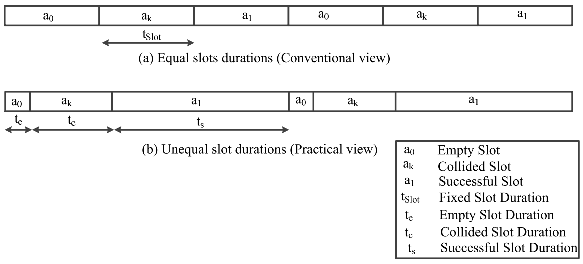

Figure 1. Equal and unequal views of slots in Frame Slotted ALOHA with frame length $L = 6$.

Increasing the reading speed can directly be translated into the maximization of the number of successful slots wrt. the number of idle or collided slots. Based on the Random Access Theory, for a given number of tags n, the expected number of empty E, successful S, and collided C slots in each frame with a length of L slots can be expressed by the following equations [3]:

$$E = L\left(1-\frac{1}{L}\right)^{n},\ S = n\left(1-\frac{1}{L}\right)^{n-1},\ C = L-E-S \tag{1}$$

The conventional definition of the expected reading efficiency η_{conv} is given by the ratio between the expected number of successful slots S in a frame and the frame length L [4]:

$$\eta_{conv} = \frac{S}{L} \tag{2}$$

Based on (1) and (2), this results in the conventional efficiency:

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

The main goal for optimizing the FSA algorithm is finding the optimal frame length L, which maximizes the reading efficiency η_{conv}. Based on (3), the reading efficiency η_{conv} is maximized when $L_{opt} = n$ as shown in [4]. In [5], [6] the authors proposed another formula for the optimal frame length that minimizes the total census delay, i.e $L_{opt} = \frac{n}{ln(2)}$. Moreover, [3] computes the optimum frame length empirically, which minimizes the reading time which almost matches the results in [5], [6]. However, in practice efficient RFID readers can quickly identify the type of a slot (i.e. idle, successful, or collided). Hence, the durations of the different slot types are not identical, which reduces the overall reading time. Figure

1 shows two frames, each one with a frame length of $L = 6$ slots. The first frame in (a) presents the conventional view of the frame with equal slots durations t_{Slot} for all slot types. The second frame in (b) presents the behavior of the real RFID slots behavior. Here, the slot duration depends on the slot type. In the recent years, some research groups concentrated on optimizing the frame length in the case of non-equal slot durations: [7], and [8], proposed a numerical solution for the optimal frame length. This method depends on searching for the optimal frame length which maximizes the reading efficiency. Moreover, this searching depends also on the tag to reader data rate, which makes the searching process more complicated. [9] optimized the mean number of resolved tags in unit time by taking into consideration the different slot durations. However, this approach bases on a complex multi-dimensional table look-up, which is relatively time consuming. [10] proposed to search for the optimum frame length that minimizes the mean time needed to resolve a bunch of tags. However, the author reached to a recursive Bellman-equation, which is complex to be applied in systems with real time restrictions. In this paper, we propose a novel closed form solution for the optimum frame length in FSA for RFID systems. The proposed solution gives a direct relation between the frame length L, and the number of tags n in the reading area. Furthermore, it includes a factor representing the different slot durations.

This paper is organized as follows: Section II presents the proposed closed form for the optimal frame length based on the Time-Aware FSA efficiency. Next, section III applies the new optimum frame size on the ISO 18000-6C standard. Finally, section IV gives numerical results on the improvements of the new optimization criterion, before we conclude in section V.

II. NEW OPTIMAL FRAME LENGTH FOR UNEQUAL SLOT DURATIONS

For calculating the proposed optimal Time-Aware frame size L_{TA}, which takes into consideration the different slot durations, we firstly have to define the Time-Aware reading efficiency η_{TA}. Let the Time-Aware reading efficiency be the ratio between the total successful time and the total frame time:

$$\eta_{TA} = \frac{t_s \cdot S}{t_e \cdot E + t_s \cdot S + t_c \cdot C}, \tag{4}$$

where $t_s \cdot S$, $t_e \cdot E$, and $t_c \cdot E$ are respectively the expected total successful, idle, and collided times. Furthermore, S, E, and C are the expected numbers of successful, empty and collided slots, and t_s, t_e, t_c are respectively the successful, idle, and collided slot durations. The next step is to derive the new optimum frame length L_{TA} under the Time-Aware environment. L_{TA} can be optimized by finding the value of L which maximizes the Time-Aware reading efficiency. This is achieved by differentiating the reading efficiency in (4) with respect to the frame length L and equate the result to zero:

$$\frac{\partial \eta_{TA}}{\partial L} = 0 \tag{5}$$

According to (1), E, S, and C are a function of L. Taking into account that t_e, t_s, t_c are constants for a given system specification, we get:

$$\frac{(t_e E + t_s S + t_c C) t_s \frac{\partial}{\partial L}(S) - t_s S \frac{\partial}{\partial L}(t_e E + t_s S + t_c C)}{(t_e E + t_s S + t_c C)^2} = 0 \tag{6}$$

After multiplying both sides by the denominator and dividing by t_s (non-zero constant), the equation can be simplified to:

$$(t_e E + t_c C)\frac{\partial}{\partial L}(S) + t_s S \frac{\partial}{\partial L}(S) = S \frac{\partial}{\partial L}(t_e E + t_c C) + t_s S \frac{\partial}{\partial L} S \tag{7}$$

After subtracting the term which is multiplied by t_s, the equation finally results in:

$$\{t_e E + t_c C\} \frac{\partial}{\partial L}(S) = S \frac{\partial}{\partial L} \{t_e E + t_c C\} \tag{8}$$

Then, substituting the values of E, S, and C from (1) leads to:

$$\begin{aligned} &\left\{ t_e \underbrace{L\left(1-\frac{1}{L}\right)^n}_{E} + t_c \underbrace{(L - \left(1-\frac{1}{L}\right)^{n-1}(L-n-1))}_{C} \right\} \\ &\qquad \times \frac{\partial}{\partial L} \underbrace{n\left(1-\frac{1}{L}\right)^{n-1}}_{S} \\ &\qquad = \underbrace{n\left(1-\frac{1}{L}\right)^{n-1}}_{S} \\ &\times \frac{\partial}{\partial L} \left\{ t_e \underbrace{L\left(1-\frac{1}{L}\right)^n}_{E} + t_c \underbrace{(L - \left(1-\frac{1}{L}\right)^{n-1}(L-n-1))}_{C} \right\} \end{aligned} \tag{9}$$

By simplifying the result, the final exact equation for the proposed Time-Aware frame length is given by the implicit equation:

$$\left(1 - \frac{n}{L_{TA}}\right) = (1 - C_t)\left(1 - \frac{1}{L_{TA}}\right)^n, \tag{10}$$

where n is the number of tags, and C_t is the slot duration constant defined as $C_t = \frac{t_e}{t_c}$ with $0 < C_t \leq 1$, as $t_e \leq t_c$ in practical applications. (10) shows the exact relation between the proposed Time-Aware frame length L_{TA} and the number of tags n, which takes into consideration the time difference in the slot durations.

Unfortunately, (10) is an implicit equation. We will now derive an approximate, but explicit equation. (10) can be also expressed as:

$$\left(1 - \frac{1}{\beta}\right) = (1 - C_t)\left(1 - \frac{1}{\beta n}\right)^n, \tag{11}$$

where $\beta = \frac{L_{TA}}{n}$. As we are focusing on systems with many tags we can use the approximation

$$\lim_{n \to \infty} \left(1 - \frac{1}{\beta n}\right)^n = e^{-\frac{1}{\beta}}, \tag{12}$$

which simplifies (10) to:

$$\left(1 - \frac{1}{\beta}\right) = (1 - C_t)\, e^{-\frac{1}{\beta}}. \tag{13}$$

Analysis of (10) indicate that the relevant values for $\beta = \frac{L_{TA}}{n}$ are in the region close to one. Hence, we can develop a Taylor series for $e^{-\frac{1}{\beta}}$ around one which leads to:

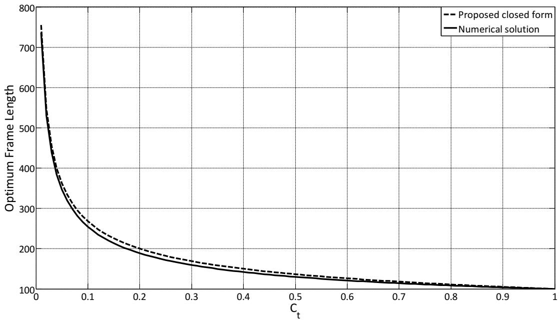

Figure 2. Optimum frame length L_{TA} as a function of the slot duration constant C_t ($n = 100$ tags). The conventional case with identical slot durations corresponds to $C_t = 1$.

$$e^{-\frac{1}{\beta}} \simeq 1 - \frac{1}{\beta} + \frac{1}{2\beta^2} \tag{14}$$

After substituting (13) and additional simplifications we get:

$$\beta^2 C_t - \beta C_t + 0.5(C_t - 1) = 0 \tag{15}$$

By solving (15), and rejecting the negative solution we finally obtain:

$$L_{TA} = \frac{n}{2}\left(1 + \sqrt{\frac{2}{C_t} - 1}\right) \tag{16}$$

(16) presents the proposed closed form equation for the optimum frame length. The proposed equation gives a linear relation wrt. the number of tags n, and includes the slot duration constant C_t, which can be easily varied as a function of the transmission rate and the working standard. According to the literature, [11] is the only author who proposed a closed form formula for the optimum frame length in the case of non-equal slots durations. The author proposed an equation depending on the LambertW function, which is a complex fuction and can not be used for further analytical analysis. Figure 2 shows the behavior of the frame lengths as a function of the slot duration constant C_t for $0 < C_t \leq 1$ and a fixed number of $n = 100$ tags using the numerical solution and the proposed closed form equation (i.e. (16)). According to figure 2, the proposed equation approaches the numerical solution in the full range of C_t. Additional analysis show that (16) already reaches precise results for $n = 10$ tags.

III. OPTIMIZED TIME-AWARE FRAME LENGTH FOR THE ISO 18000-6C PROTOCOL

This section applies the timings of the ISO 18000-6C standard [1] – the most widely used standard for commercial RFID systems – on the proposed optimization criterion. Figure 3 shows the timings of the different slot types. Each slot contains different sequences of reader to tag commands and tag replies. The duration of each slot is described in the following:

- Successful slot: In a successful slot the reader begins with a query command. After the time T_1, one tag responds with a reply containing the so-called RN16 number. As soon as the reader recognizes this RN16, it waits for time T_2 and sends an acknowledgment command to the tag, asking the tag for its EPC code, which contains the actual payload data. After the time T_1, the tag sends its EPC code to the reader. Finally, the reader waits for the additional time T_2 and then proceeds to the next slot. This results in the overall slot duration t_s:

$$t_s = T_q + 2\,T_1 + T_{RN16} + 2T_2 + T_{Ack} + T_{EPC} \tag{17}$$

- Collided slot: In a collided slot, the reader also starts with a query command. Multiple tags start to respond after the time T_1. Due to the resulting collision, the reader is not able identify any of these tags. Hence, the reader directly starts a new slot after time T_2. This results in the overall slot duration t_c:

$$t_c = T_q + T_1 + T_{RN16} + T_2 \tag{18}$$

- Idle slot: In this slot type, the reader sends a query command to the tags, and waits for time T_1. However, the reader receives no reply. Therefore, the reader terminates the slot after the additional waiting time T_3. This results in the slot duration:

$$t_e = T_q + T_1 + T_3 \tag{19}$$

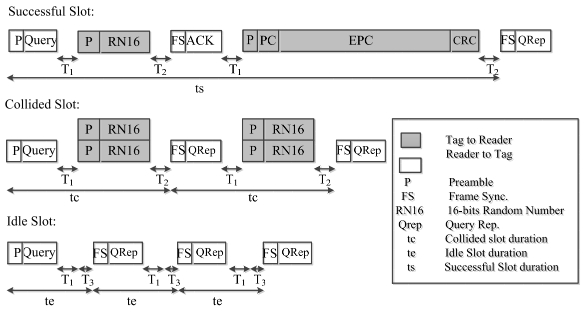

Figure 3. Slot durations during tag inventory rounds for the ISO 18000-6C standard

According to (17), (18), and (19), and based on the timing values of the ISO 18000-6C standard [1] (assuming a typical data rate 60 kbps), we obtain the following typical slot durations: $t_s = 3606.5\,\mu s$, $t_c = 850\,\mu s$, and $t_e = 175\,\mu s$. This finally leads to the constant $C_t = 0.2$. Based on (16), the optimum frame length should be $L_{TA} = 2n$, which is almost twice the length of the conventional optimum frame length. These results are confirmed by the results presented in [9], [10] using different performance metrics. However, unlike the complex table loop-up presented in [9], [10], our approach only bases on a linear equation, which is a function of the number of tags n.

IV. SIMULATION RESULTS

Figure 4 shows simulation results for the reading time reduction of the proposed optimal Time-Aware frame length L_{TA} wrt. the classical optimal frame length $L = n$ as a function of the slot duration constant C_t. These simulations assume a perfect knowledge of the number of tags n. According to the figure, $C_t = 0$ means that the idle slot duration time t_e is quite small wrt. the collided slot duration time t_c. In this case, the proposed Time-Aware frame length can reduce the average reading time by up to 12% compared to the conventional optimization criterion. With $C_t = 1$, which means that the slot durations are of identical length, we obtain the efficiency of the

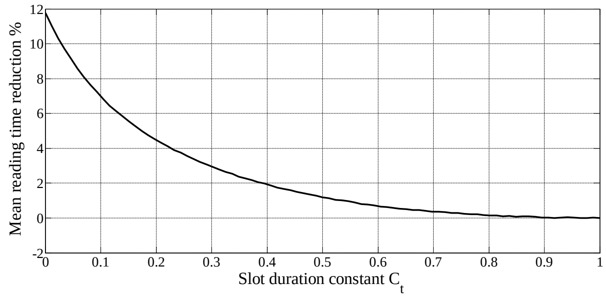

Figure 4. Percentages of saving time using the proposed TAFSA for an ideally known number of tags (1000 iterations for each step)

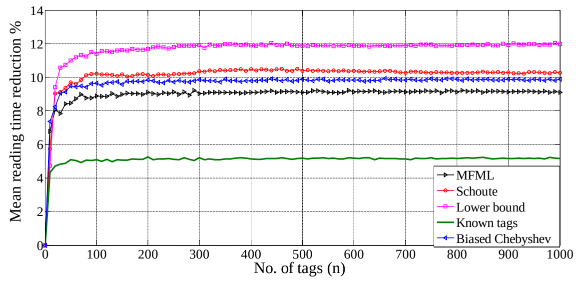

Figure 5. Percentages of saving time using the proposed TAFSA for different anti-collision algorithms (1000 iterations for each step)

classical optimization, i.e. $L = n$. According to the results in section IV, the slot duration constant for ISO 18000-6C standard is $C_t = 0.2$. In this case we can expect an average reading time reduction of $5\,\%$.

In practice, the number of tags in the interrogation region is unknown. Hence, the anti-collision algorithms in real RFID systems consist of two stages: The first stage estimates the number of tags in the interrogation area $\hat{n}$. The second stage calculates the optimal frame length L_{opt} based on $\hat{n}$ for maximizing the reading efficiency. Figure 5 shows the mean reduction of the reading time using the proposed Time-Aware frame length for some well-known tag estimation algorithms assuming the ISO 18000-6C protocol parameters with $C_t = 0.2$. The main issue of these simulations is to show the practical effect on the reading time by working with the proposed frame length using different tag estimation algorithms. Each curve presents the mean reduction of the reading time between the proposed frame length and the conventional frame length using the same estimation algorithm. When a simple tag estimation technique is used like Lower bound [3] or Schoute [12], we can reduce the reading time in the order of 10 to $12\,\%$, and we gain around $9\,\%$ for better estimation algorithms like MFML [13] and Biased Chebyshev [14]. According to figure 5, in case of better estimation algorithms, the mean reading time reduction approaches the curves assuming perfect knowledge of the number of tags. As a result, the newly proposed closed form algorithm provides additional improvements wrt. the classical optimization algorithm when the tag estimation provides inaccurate results.

V. CONCLUSION

This paper proposes a novel closed form solution for the optimum frame length in unequal slot duration FSA. The theoretical derivations lead to a new optimization criterion that can be easily implemented in RFID readers. The proposed frame length equation gives the most accurate results compared to the exact solution, and the numerical methods. However, we propose a direct linear relation with the number of tags in the reading area. The proposed optimization method reduces the average reading time by $5\,\%$ in case of a perfect knowledge of the number of tags. In realistic systems, where the number of tags has to be estimated, the gain reaches up to $12\,\%$.

The future work will especially focus on additional improvements, if the exact number of tags is unknown, and the initial frame size is optimized.

ACKNOWLEDGMENT

The authors are grateful to department OK at Fraunhofer IIS in Erlangen, Germany, for the support of this work.

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