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# Effect of Slot Type Identification on Frame Length Optimization

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***Abstract*—In dense radio frequency identification (RFID) systems, reducing reading times is crucial. For tag anti-collision management, most RFID systems rely on frame slotted ALOHA (FSA). The most common method to reduce the reading time for large tag populations is optimization of the number of slots per frame. The slot duration in real RFID systems is determined by the slot type (idle, successful, or colliding). Furthermore, by detecting the strongest transponder, colliding slots can be transformed to successful slots, a phenomenon known as the capture effect. Additionally, RFID readers might be capable of identifying slot types using the physical layer which reduces the colliding slot time because at this moment the reader can immediately terminate the connection as there is no need to reply with invalid acknowledge and wait for the time-out. In this paper, we provide a novel approach for analytical estimation of the optimal frame length. Our approach yields a novel closed form equation for the frame length that takes into account durations of different slot types, the capture effect, and the probability of slot type identification. Experimental results for FM0 encoding show that our technique achieves a total reading time reduction between 5.5% and 11.3% over methods that do not take into account slot type identification. However, the reduction in reading time is maximally 9%, 6%, and 1% for Miller encoding scheme with $M = 2, 4$, and 8, respectively.**

## I. Introduction

The number of applications using Radio-Frequency Identification (RFID) has increased in recent years, and it is expected that this number will continue to rise in the near future. One of the most common use cases is in logistics, where hundreds of tags (transponders) can be placed on pallets in close proximity. This requires fast RFID readers so as not to delay the delivery of the actual items. Common RFID standards in the logistics industry (e.g., EPCglobal Class-1 Gen-2 (EPC) standard [1]) are TDMA-based (Time Division Multiple Access). The tags in commercial RFID systems must be inexpensive and are not able to detect the channel or communicate with other tags. As a result, in dense scenarios with many tags, the probability of collisions increases. Therefore, readers are responsible for efficiently coordinating the network by applying specific anti-collision algorithms. The anti-collision algorithm of the EPCglobal C1 G2 standard [1] is based on Framed Slotted ALOHA (FSA) [2]. The frame length (i.e., the number of slots available in the frame) is broadcast to the tags by the reader. Each tag then randomly selects one of the available slots and responds to the reader within that slot. Using this approach, the reader can successfully decode the data in a particular slot only if a single tag responded within that slot. Such slots are called *successful*. In addition, there are *empty* slots with no tag responses and *colliding* slots with multiple tag responses. Typically, the reader is unable to detect all tags in range using a single frame due to collisions. As a result, to read all tags multiple frames are used. Hence, the conventional reading efficiency $\eta_{conv}$ within a single frame of length $L$ can be defined as [3]:

$$\eta_{conv} = \frac{S}{E+S+C} \tag{1}$$

where $E$, $S$, and $C$ are the expected number of empty, successful, and collided slots, respectively. For a given tags population $n$, the main objective of the EPCglobal C1 G2 anti-collision algorithm is to find the optimal frame length $L$ that maximizes the reading efficiency $\eta_{conv}$ [3]. The maximum reading efficiency is 36% for conventional RFID receivers with no collision recovery capabilities [4]. This efficiency level can be achieved at $L = n$.

This assumption is not accurate enough as it ignores many practical concerns. One of these concerns is the near-far problem which is very common in passive RFID systems [5]. A tag closer to the reader will respond at a much higher level than tags that are farther away. Even in the case of a colliding slot, the reader would in many cases be able to decode the closest tag's response. This phenomenon is known as the *capture effect* [4]. Another significant concern is duration of different slots. The conventional reading efficiency definition in (1) assumes that empty, successful, and collided slots all have the same duration. However, in real RFID systems, these vary greatly depending on the slot type as shown in Fig. 1. [4]. Finally, receiver's capability to identify collided slots is omitted in Eq. (1). Identification of the collided slots defines two new slot types; *identified collided* slot with duration of $t_{ci}$ and *non-identified collided* slot with duration of $t_{cn}$ as shown in Fig. 1. The identified collided slot is detected by the reader and it might be converted to successful slot or not based on the position of the colliding objects and the collision recovery capability of the reader. The non-identified colliding slot is not detected by the reader and it might be considered as a successful slot directly due to the capture effect or as invalid slot due to wrong acknowledgement as shown in Fig. 1. Invalid slot occurs when the reader wrongly detects the tag reply and then acknowledges the non-existent tag with faulty acknowledgement. At that moment, no tags will reply to this acknowledgement and the reader will wait for a specific time-out and start over the reading process. The main contribution of this paper are as follows:

- A novel closed form expression for optimizing frame lengths that considers the capture effect, slot timing differences, and slot type identification capability;
- Careful performance evaluation of our optimized frame length with different tag encoding schemes.

The paper is organised as follows. Section II introduces relevant related work. In Section III, the proposed optimum frame length estimation is derived. Experimental results are discussed in Section IV and Section V concludes the paper.

## II. Related Work

Previous efforts on frame length optimization reported in the literature can be divided into three categories: The first category takes into account only the capture probability for the frame length optimizations such as [5]. The second category considers only the differences in slots timing, such as [6]–[8]. The final category, optimizes the frame length taking into account the capture probability and the difference in the slots timing [4], [9]–[11]. Some of these optimizations are captured by numerical expressions [9], [10], while the rest use closed form solutions [4], [6]–[8], [11]. None of them, however, considered RFID reader's capability to identify collided slots although the collision recovery capability of the receiver was considered [11]. Receiver able to identify slot types will need shorter total reading time. Nevertheless, the total reading time can be additionally reduced by optimizing the frame length considering this ability as addressed here.

## III. Slot Type aware Frame Length Optimization

Frame length optimisation can be achieved by improving the overall reading efficiency. 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 [3]:

$$E = L\left(1-\frac{1}{L}\right)^{n}, S = n\left(1-\frac{1}{L}\right)^{n-1}, C = L-E-S \quad (2)$$

The conventional definition of the expected reading efficiency $\eta_{conv}$ is given by the ratio between the expected number of successful slots $S$ in a frame and the frame length $L$ as shown in (1). Using (1) and (2), we obtain the conventional efficiency:

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

In [8], the frame length is optimised by giving a new definition for the reading efficiency, e.g., the Time-Aware reading efficiency $\eta_{TA}$. It is the ratio between the total successful time and the total frame time:

$$\eta_{TA} = \frac{t_s \cdot S}{t_e \cdot E + t_s \cdot S + t_c \cdot C} \quad (4)$$

where $t_s \cdot S$, $t_e \cdot E$, and $t_c \cdot E$ are respectively the expected total successful, idle, and collided times. Considering the capture effect with a capture probability $\alpha$, the $E$, $S$, and $C$ actual values have to be converted to $E_c$, $S_c$, and $C_c$, respectively [4]. Their relation is given by:

$$E_c = E,\; S_c = S + \alpha \cdot C,\; C_c = (1-\alpha)\cdot C. \quad (5)$$

Basically, collided slots are converted to successful slots with probability $\alpha$. From (5), the time and capture probability aware efficiency can be written as:

$$\eta_{TCA} = \frac{t_s \cdot S_c}{t_e \cdot E_c + t_s \cdot S_c + t_c \cdot C_c}. \quad (6)$$

From (6), the optimum frame length is derived to be [4]:

$$L_{TCA} = \frac{n}{2}\left((1-\alpha) + \sqrt{(1-\alpha)^2 + \frac{2}{C_t}(1-\alpha)\cdot(1-C_t)}\right). \quad (7)$$

where $C_t = \frac{t_e}{t_c}$ $(0 < C_t \leq 1)$, as $t_e \leq t_c$ in practical applications. Clearly (6) ignores RFID reader's slot type identification capability as $t_{ci} = t_{cn} = t_c$ is assumed. By taking into account the capability of identifying collided slots, (6) can become:

$$\eta_{STI} = \frac{t_s \cdot S_c}{t_e \cdot E_c + t_s \cdot S_c + t_{ci} \cdot C_{ci} + t_{cn} \cdot C_{cn}} \quad (8)$$

where $C_{ci}$ and $C_{cn}$ are the expected numbers of identified and non-identified collided slots respectively. Let us define a new parameter which is the STI success probability, $\gamma$:

$$\gamma = \frac{C_{ci}}{C_c} \quad (9)$$

Because the total number of collided slots is constant, hence:

$$C_c = C_{ci} + C_{cn} \quad (10)$$

Considering (9) and (10), (8) can be written as:

$$\eta_{STI} = \frac{t_s \cdot S_c}{t_e \cdot E_c + t_s \cdot S + \underbrace{(t_{cd} \cdot \gamma + t_{cn} \cdot (1-\gamma))}_{\grave{t}_c} \cdot C_c} \quad (11)$$

It can be observed that (11) is very similar to (6) except $t_c$ can be replaced by $\grave{t}_c$. Hence, the optimum frame length taking into consideration the STI is:

$$L_{STI} = \frac{n}{2}\left((1-\alpha) + \sqrt{(1-\alpha)^2 + \frac{2}{C_{STI}}(1-\alpha)\cdot(1-C_{STI})}\right), \quad (12)$$

where $C_{STI} = \frac{t_e}{\grave{t}_c}$. $\gamma$ can be obtained during the identification process as shown in (9). Eq. (12) depends on $n$ that can be estimated using any kind of cardinality estimation algorithm [3], [12], [13].

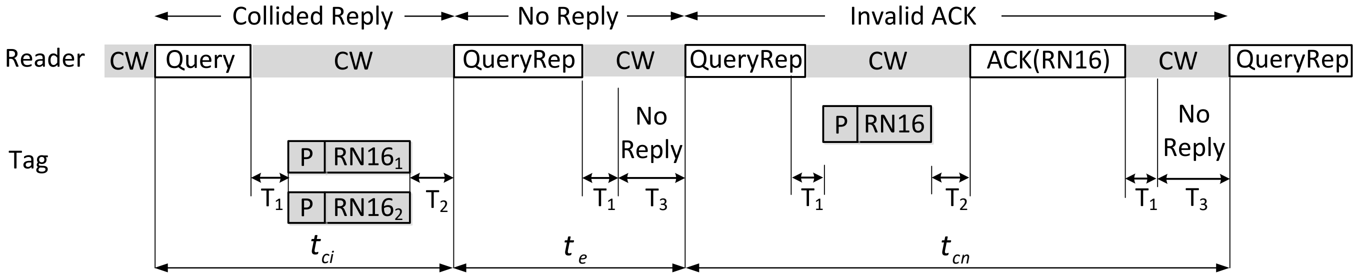

Fig. 1: Block diagram of the proposed RFID reader model with STI capability.

TABLE I: Slots timing for different encoding schemes

| BLF = 640 kHz | FM0 | Miller ($M = 2$) | Miller ($M = 4$) | Miller ($M = 8$) |
|---|---|---|---|---|
| $t_s$ | 1 ms | 1.3 ms | 1.8 ms | 2.7 ms |
| $t_{cd}$ | 0.22 ms | 0.28 ms | 0.4 ms | 0.63 ms |
| $t_{cn}$ | 0.55 ms | 0.61 ms | 0.73 ms | 0.96 ms |
| $t_e$ | 0.21 ms | 0.21 ms | 0.21 ms | 0.21 ms |

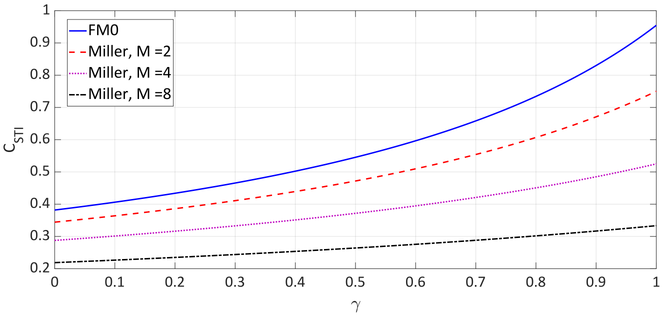

Fig. 2: Effect of capture probability on the timing ratio, $C_{STI}$ for FM0 and Miller encoding schemes of $M = 2$, 4 and 8.

## IV. Experimental Results

In this section we present simulation results to validate the benefits of the proposed STI capability aware frame length optimization technique. In our experiments we assume $n = 250$, a number of tags representative for a dense scenario. The timing of different slots for several tag encoding schemes at Back-scatter link frequency (BLF) of 640 kHz can be obtained based on [8] and is depicted in Table I. A new performance metric is defined here to quantify the reading time improvements as a result of employing the proposed technique, referred to as *reading time reduction*. The reading time reduction is defined as the difference between the time needed to read all tags using the frame length in (7) and (12) over the time needed to read all tags using the frame length in (7) times 100%. Fig. 2 illustrates the effect of the slot type identification probability, $\gamma$ on the timing ratio, $C_{STI}$ for the different encoding schemes considered. Generally, it is clear that the effect of the slot type identification on FM0 encoding is greater than for Miller. In case of the Miller encoding scheme, the ratio

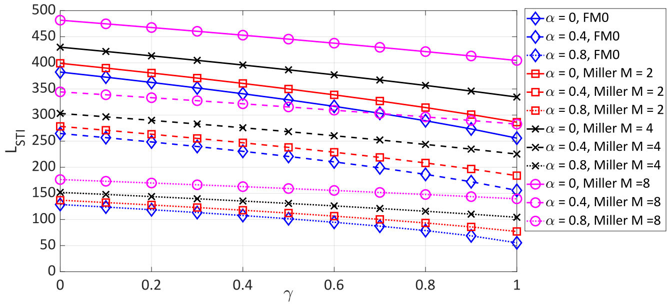

Fig. 3: Effect of capture probability on the optimum frame length, $L_{STI}$ for FM0 and Miller schemes of $M = 2$, 4 and 8.

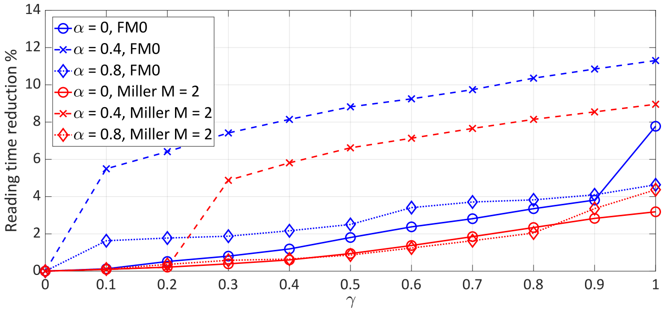

Fig. 4: Reading time reduction for 250 tags using FM0 and Miller encoding ($M = 2$) for different capture probabilities.

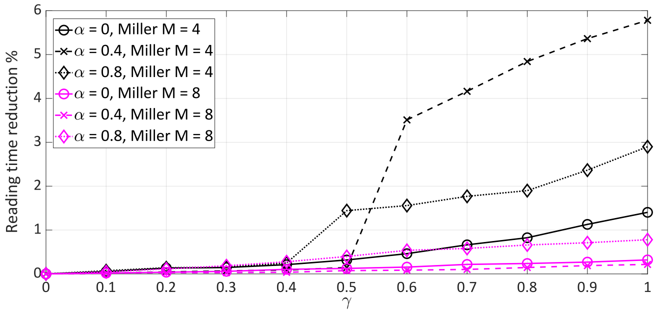

Fig. 5: Reading time reduction for 250 tags using Miller encoding ($M = 4$, and 8) with different capture probabilities.

between the successful slot and collided slot is larger than the equivalent one when FM0 is used as shown in Table I. In other words, when Miller encoding schemes are used, the total reading time is dominated by the successful slots because the duration of the tag reply will be very long with respect to the reader commands [8]. This effect scales with $M$ because the length of successful slot increases. Hence, the effect of slot type identification diminishes as $M$ decreases. Fig. 3 shows the effect of the slot type identification on the optimal frame length when the collision recovery capability of the reader is taken into account. As expected, the figure shows that the optimal frame length, $L_{STI}$ decreases as the collision recovery probability, $\alpha$ increases [4]. Additionally, the variation in $L_{STI}$ with respect to $\gamma$ is the highest in case of FM0 encoding. The variation decreases as $M$ increases in case of Miller because the timing ratio, $C_{STI}$ gets closer to unity as $M$ increases as shown in Table I.

Figures 4 and 5 show that as $\gamma$ increases as the reading time reduction grows. This is expected since the reader capability to identify the slot will improve. Moreover, the reading time reduction of FM0 is larger than the reading time reduction of Miller. This is because the ratio between the non-detected collided slot $t_{cn}$ and the detected collided slot $t_{ci}$ decreases for larger $M$ as shown in Table I. However, at $\alpha = 0$ and 0.8, the reading time reduction is less than 8%. At high values of $\alpha$, the capture effect dominates, hence, the reading time might decrease because the receiver has the capability of recovering the colliding slots. Therefore, the effect of using the optimal formula decreases. In absence of the capture effect, the saving time decreases because one of the parameters in (7) and (12) is eliminated. In other words, when the reader has a collision recovery capability, it can benefit more from slot type identification than otherwise. This is because some of these identified slots can be recovered and converted to successful slots. Hence, the effect of the new optimized frame length diminishes. At moderate values of $\alpha$, our proposal shows its optimal performance. In real scenarios, $\alpha$ will have moderate values that strongly depend on the signal to noise ratio at the receiver which is a crucial parameter in any estimation algorithm [14], [15].

## V. Conclusions

We proposed a novel closed form expression for determining the optimal FSA frame length analytically. The effects of non uniform slot durations, the presence of capture effects, and RFID readers with slot type identification capabilities were all considered. Our approach can be used for improving the reading speed of real-life RFID systems in scenarios with large number of tags present within the reading range. Frame length optimisations taking into account non-uniform slot durations along with the capture effect has been previously addressed. However, the slot type identification was not considered in the optimization process as proposed in this paper. Our frame length optimization improves the reading time of the RFID reader under all tag encoding schemes. The proposed algorithm showed a total reading time reduction between 5.5% and 11.3% for FM0 encoding scheme widely used in real systems due to its highest data rate. However, the maximum reduction in reading time is 9%, 6%, and 1% for Miller encoding scheme with $M = 2, 4$, and 8, respectively. It is clear that the improvement diminishes as $M$ increases for Miller encoding scheme because the duration of the tag reply is linearly related to $M$ which means the tag reply when Miller of $M = 2$ is double the tag reply of FM0. Using the proposed technique would minimize invalid slots which send wrong acknowledgement commands. This is done by identifying the colliding slot from the RN16 responses used by the tags to reserve slots. Hence, the wrong acknowledgement will not be sent and the transaction will just end. However, in case of Miller encoding with $M = 8$ the length of the tag reply is much longer than the acknowledgement command. Therefore, reading time reduction is small.

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