OFSA: Optimum Frame-Slotted Aloha for RFID Tag Collision Arbitration

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Abstract

RFID technologies have attracted a lot of attention in recent years because of their cost/time-effectiveness in large-scale logistics, supply chain management (SCM) and other various potential applications. One of the most important issues of the RFID-based systems is how quickly tags can be identified. Tag collision arbitration plays a more critical role in determining the system performance especially for passive tag-based ones where tag collisions are dealt with rather than prevented. We present a novel tag collision arbitration protocol called Optimum Frame-Slotted Aloha (*OFSA*). The protocol has been designed to achieve time-optimal efficiency in tag identification through an analytic study of tag identification delay and tag number estimation. Results from our analysis and extensive simulations demonstrate that *OFSA* outperforms other collision arbitration protocols. Also, unlike most prior anti-collision protocols, it does not require any modification to the current standards and architectures facilitating the rollout of RFID systems.

Keywords: Collision resolution, RFID, frame-slotted Aloha, tag anti-collision, tag identification.

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1. Introduction

Radio Frequency IDentifier (RFID) is a contactless and automatic identification system [1], which is rapidly becoming the technology of choice to enable cost/time-effective service in various industrial applications, such as factory automation, electronic point of sales (e-POS) systems, and the advanced management of supply chain and logistics networks. An RFID system consists of a reader and tags. A tag sends its identifier (ID) to a reader, and then the reader sends RF signal to the tag. Once identified, the reader can read or write data by using the tag's identifier. RFID tags are classified into active and passive tags depending on whether they can communicate using their own power or not. An active tag, similar to a sensor node in WSNs, has its own power. On the other hand, a passive tag makes use of power from a reader's RF signals. Although they have limited capabilities, passive tags are widely adopted for RFID systems due to the advantages of low deployment costs. Therefore, we consider only a passive tag for this paper.

In the presence of multiple readers/tags, RFID system performance relies on its collision arbitration scheme that coordinates competing media accesses among them. However, due to the low-cost constraint of passive tags, it is inappropriate to simply employ media access control schemes, such as frequency division multiple access (FDMA) or code division multiple access (CDMA), for RFID systems. Considerable research efforts have been made on the collision arbitration protocols to reduce identification delay for densely deployed passive tags [2][3].

Tag collision arbitration protocols are divided into depth first search (DFS) and breadth first search (BFS) mechanisms. DFS and BFS mechanisms correspond to tree-based and Aloha-based tag anti-collision protocols, respectively. In the tree-based protocols, a binary tree protocol using a counter and random generator is applied in ISO/IEC 18000-6 type B [4]. A query tree protocol reducing the memory in tags by employing the prefix of tag ID has also been proposed [5]. Our previous work [6] explored tree-based anti-collision protocols that can quickly track tags. [7] suggested a tree-based scheme that enables the early shutdown of a collision slot. The work delivered remarkable improvements to tree-based protocols by reducing unnecessary collisions. Nevertheless, it is well known that tree-based protocols have a disadvantage that they should use relatively bigger messages compared to Aloha-based ones. In addition, the expected efficiency of the used slots is not as good as that of Aloha-based ones. In the case of Aloha-based anti-collision protocols, a frame-slotted Aloha (FSA) protocol, which is an extension to a pure Aloha protocol [2], is widely being used in RFID standards [4][8][9][10]. In recent years, adaptive FSA protocols, where frame sizes are adaptively adjusted, have actively been pursued [11][12][13][14][15][16]. Lastly, as a part of the effort to improve FSA protocol, we introduced Time-optimal protocol in our latest work [17].

Despite a variety of FSA protocols being used by RFID standards, most of them are concerned about the minimization of slot delay; no *global optimization of identification time delay* has been reported in the literature. In this paper, as extending our previous work to incorporate further analysis of the performance sensitivity and the optimality, we propose a novel RFID tag anti-collision protocol called optimum FSA (*OFSA*) protocol. To our best knowledge, we are the first on who develop an analytical model for tag identification delay. Based on the analytical model, optimum frame size is derived. Theoretical analysis and simulation results indicate that *OFSA* significantly reduces tag identification delay compared to other anti-collision protocols.

The remaining of this paper is organized as follows. In Section 2, the system model is described, and related work is summarized. Our optimum FSA protocol is presented in Section 3. Theoretical analysis and simulation results are given in Sections 4 and 5, respectively. Finally, Section 6 concludes this paper.

2. System Model and Related Work

In this section, we describe the system model and review related work on adaptive FSA protocols.

2.1 System Model

Adaptive FSA protocols perform tag identification in the unit of slots and frames. A frame consists of multiple slots, and the frame size is determined by the reader. For tag identification, a tag chooses a slot within a frame. The reader helps tags to know the starting points of slots by sending messages for synchronization so that tags can pinpoint their turns. When a tag transmission occurs in a slot, the reader can determine whether or not the transmission was successful by checking cyclic redundancy code (CRC). If there is no transmission from tags, a slot is identified as an idle slot. If a tag fails to be identified due to collision in the slot, the tag should wait for the next frame. Key factor to determine the next frame size is the number of unidentified tags. Hence, the reader keeps a record of unidentified tags, and uses them to calculate the next frame size.

2.2 Related Work

Recently a set of RFID collision arbitration schemes for improving the efficiency of adaptive FSA protocols have been proposed in the literature [11][13][14][16]. Theses protocols consist of two major parts: tag number estimation and frame size adaptation.

Vogt [14] proposed two tag number estimators. First, a tag number estimator was developed under the assumption that the number of tags in a reader's range is at least two times of the number of collision slots. After that, Vogt proposed another tag number estimator that returns the number of tags with the minimum distance from the vector composed of the statistics on each slot, using the characteristic of Chebyshev's inequality. In addition, Vogt suggested the optimal frame size adaptation scheme based on identification time delay measured in NXP's I-CODE (ISO-15693) RFID system [18]. Zhen et al. [16] used the tag number estimator, where the number of tags in a reader's range is assumed 2.39 times of the number of collision slots that is first reported in [13]. Zhen demonstrated that the efficiency in terms of slot utility is optimal when a frame is adjusted according to the number of unidentified tags. Cha et al. [11] proposed a collision-based tag number estimator, which uses a comparison between the collision rate in a frame and the collision probability of a slot. Similarly to [16], Cha et al. [11] assumed the integer frame size. More recently, Khandelwal et al. [19] devised a frame size adaptation scheme designed for a variant system of STAC system [8].

To quantify the efficiency on identified tags, [11] and [16] used the information on how many slots are used. That is, slot-efficiency is a key parameter to be optimized. However, this cannot be a generic metric, because the time duration of each slot varies in different standards or systems, and the slot time duration is dependent on the identification result (i.e., success, idle, and collision). For example, since EPCglobal Class-1 Generation-2 standard uses RN16 (16bit-sized random number generated by a tag) instead of tag ID, the duration of a success slot is 5 times longer than the duration of a collision slot. In addition, the duration of an idle slot can be significantly shortened because a reader does not waste time to wait tags' answers.

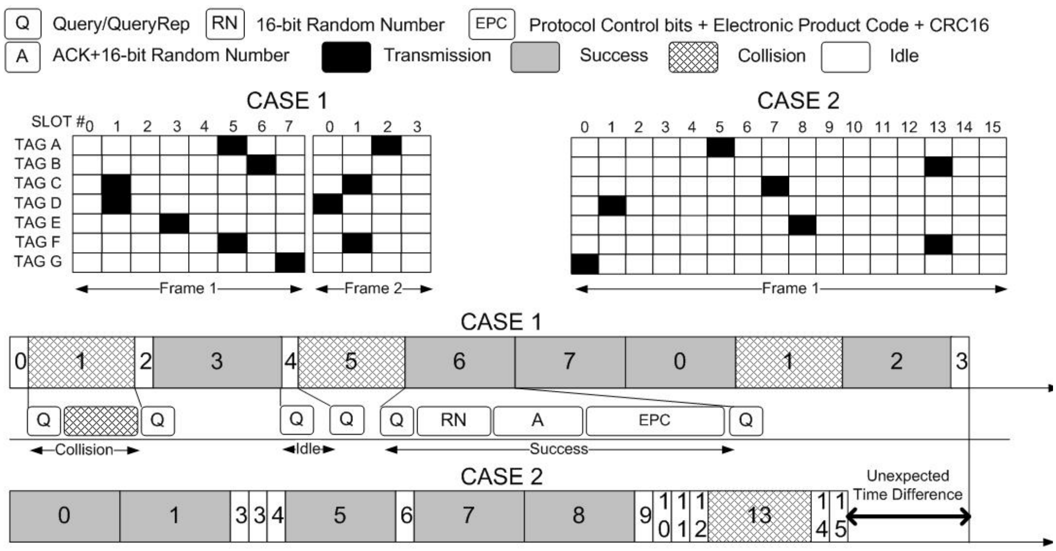


Fig. 1. An identification process example to illustrate the slot-time anomaly: two slot-optimal frames in CASE 1 show much better slot-efficiency ($5/12 \approx 0.417$) than a frame in CASE 2 ($5/16 \approx 0.313$), however, actually, CASE 2 outperforms CASE 1 in time-performance. The environment is assumed to be EPCglobal Class-1 Generation-2.

Fig. 1 depicts an example in which the metric based on "slot-optimality" misleadingly interprets tag identification efficiency in EPCglobal Class-1 Generation-2 RFID communications. In terms of slot efficiency, the total throughput of 2 frames in CASE 1 is $5/12 \approx 0.417$, which is higher than that of 1 frame in CASE 2 ($5/16 \approx 0.313$). On the other hand, in terms of time-efficiency, CASE 2 outperforms CASE 1. With early insights into the phenomenon, we name this problem as the *slot-time anomaly*. Including [11] and [16] stated above, existing adaptive FSA protocols have focused on improving the slot-efficiency [12][13][15]. Since the RFID systems can be used in various target environments and under different operating conditions (which means different slot durations), time efficiency can be a more practical and precise metric than slot efficiency to quantify the protocol performance.

Another problem with the current protocols is that they cannot be directly applied to the existing standards without modifying tag architecture. For instance, [11], [13] and [16] considered only frame sizes of integer, whereas the RFID standards direct that frame size adaptation should be conducted only for frame sizes with powers of 2. Considering given limitations on the low cost of RFID tags, it is inevitable that protocols which requires tag modification have a deployment issue in real world. Furthermore, some protocols are designed to conduct optimal adaptation only for specific systems. For example, since the frame size adaptation of [14] was optimized based on the experimental study in an I-CODE system, it might be difficult to expect the same optimal function from other systems (e.g., ISO/IEC 18000-6 type C widely used). To tackle preceding problems we confronted, we devise a novel tag collision arbitration protocol *OFSA* which maximizes adaptiveness for contemporary RFID standards.

To the best of our knowledge, *OFSA* is the first RFID tag anti-collision protocol which identifies and addresses the *global optimization of identification time delay*.

3. Optimum FSA Protocol

Focusing on the time efficiency, we propose the optimum FSA protocol. We first derive the analytical expression for the tag identification delay. After that, we describe the optimum FSA protocol featuring two main components: frame size adaptation based on the analytical model and tag number estimation based on experimental studies.

3.1 Tag Identification Delay Analysis

Given m tags and frame size f (in numbers of slots), the tag identification delay (or the time duration between two successfully identified tags) in a frame is as follows.

$$\mathcal{D}_{Tag|m,f} = \frac{\tau_{m,f}}{f \cdot p_{succ|m,f}} \tag{1}$$

where $\tau_{m,f}$ and $p_{succ|m,f}$ represent the expected duration of a frame (in units of μs) and the probability of successful identification in a slot, respectively. In [14], *a priori* probability distribution with random variable X that represents the number of tags occupied in a slot for transmission was derived as

$$Pr_{m,f}\left(X=r\right)=\binom{m}{r}\left(\frac{1}{f}\right)^{r}\left(1-\frac{1}{f}\right)^{m-r}. \tag{2}$$

Using (2), the probability that a slot in a frame size f is a success, idle or collision is given by

$$p_{succ|m,f} = Pr_{m,f}\left(X=1\right)=\frac{m}{f}\left(1-\frac{1}{f}\right)^{m-1}, \tag{3}$$

$$p_{idle|m,f} = Pr_{m,f}\left(X=0\right)=\left(1-\frac{1}{f}\right)^{m}, \tag{4}$$

$$p_{coll|m,f} = Pr_{m,f}\left(X\geq 2\right)=1-\left(1-\frac{1}{f}\right)^{m}\left(1+\frac{m}{f-1}\right). \tag{5}$$

Then the expected number of success, idle, and collision slots is denoted by the forms as $p_{[\cdot|m,f]} \times f$. Hence, the expected duration of a frame $\tau_{m,f}$ can be obtained from

$$\tau_{m,f} = f \cdot p_{succ|m,f} \cdot T_{succ} + f \cdot p_{idle|m,f} \cdot T_{idle} + f \cdot p_{coll|m,f} \cdot T_{coll} \tag{6}$$

where T_{succ}, T_{idle}, and T_{coll} is the time duration of success, idle, collision slot, respectively. By (3)-(6), (1) can be rewritten as

$$\begin{aligned}\mathcal{D}_{Tag|m,f} &= \frac{f \cdot p_{succ|m,f} \cdot T_{succ} + f \cdot p_{idle|m,f} \cdot T_{idle} + f \cdot p_{coll|m,f} \cdot T_{coll}}{f \cdot p_{succ|m,f}} \\ &= T_{succ} + \left(\left(\gamma-1\right)\left(1-\frac{1}{f}\right)+\frac{f}{m}\left(1-\frac{1}{f}\right)^{1-m}-1\right)\cdot T_{coll}\end{aligned} \tag{7}$$

where γ is $\frac{T_{idle}}{T_{coll}}$.

3.2 OFSA Protocol

Retaining the analysis of the preceding subsection, we now deduce the details of how to compute the frame size and tag number to guarantee the optimal tag identification time delay in the *OFSA* protocol.

3.2.1 Frame Size Adaptation

Total identification time is defined as a summation of frame durations until all tags are identified. Therefore, we can optimize the total identification time by minimizing tag identification delays in each frame. Given the number of tags, we can determine the optimum frame size by the objective function below,

$$\operatorname*{argmin}_{f} \mathcal{D}_{Tag|m,f} = T_{succ} + \left((\gamma - 1)\left(1 - \frac{1}{f}\right) + \frac{f}{m}\left(1 - \frac{1}{f}\right)^{1-m} - 1 \right) T_{coll}. \quad (8)$$

To solve this optimization problem, we consider two cases: 1) when the frame size f is an (positive) integer; or 2) when it is powers of 2.

3.2.1.1 Frame Size of Integer

To show the relationship between f and the given tag number m, we differentiate the objective function (8) since the objective function holds the convexity for f (see Appendix A. (1)). As the inverse function of the derivative of the function on f does not exist, we need to examine the derivative of the objective function with respect to m (note that the object function in (8) also holds the convexity for m, as shown in Appendix A. (2))

$$\operatorname*{argmin}_{f} \mathcal{D}_{Tag|m,f} = T_{coll} \cdot \left[-\frac{1}{m^2}\left\{ f\left(1 - \frac{1}{f}\right)^{1-m} - (f-1)(\gamma - 1) \right\} - \frac{1}{m}\left\{ \left(1 - \frac{1}{f}\right)^{1-m} \cdot f \cdot \ln\left(1 - \frac{1}{f}\right) \right\} \right]. \quad (9)$$

Then, the relationship of m and f when $\frac{\partial \mathcal{D}_{Tag|m,f}}{\partial m} = 0$ is given by

$$m = -\frac{1 + \mathrm{W}\left(\frac{\gamma - 1}{\mathrm{e}}\right)}{\ln\left(1 - \frac{1}{f}\right)} \quad (10)$$

where W(·) denotes Lambert's Omega function [20]. Arranging this equation with respect to f, we obtain the following relationship,

$$f^* = \left\lfloor \left\{ 1 - \mathrm{e}^{-\left[1 + W\left((\gamma - 1)/e\right)\right]/m} \right\}^{-1} \right\rfloor \quad (11)$$

From (11), it can be shown that only m and γ determine the optimal frame size. That is, the determination of optimal frame size only depends on the number of tags and the ratio of the duration of an idle slot to a collision slot.

3.2.1.2 Frame Size with Powers of 2

In general, FSA protocol-based RFID standards are restricted to use only powers of 2 for frame sizes in order to reduce the error rate of messages from a reader and to minimize transmission delay. In this case, the optimization problem with an objective function (8) can be reduced to a non-linear integer programming (NLIP) problem. Then, an optimum frame size can be determined by comparing the two power values adjacent to the integer solution obtained from (11), because (8) holds the convexity. However, a reader cannot afford Lambert's Omega function if it is a mobile device with limited computation capability. In such a system, we can solve the integer programming (IP) problem with computational complexity of $O(\log_2 n)$, by using a bisection search algorithm. For instance, in the EPCglobal Class-1 Generation-2 standard, the total possible number of frame sizes is 16, from 2^0 to 2^{15}. Then the maximum computational cost becomes $\log_2 16 = 4$. In short, the optimal frame size can be found by only maximum 4 iterations.

3.2.2 Tag Number Estimation

To find the optimal frame size, it is needed to clarify the number of tags within a reader's identification range. Several methods are used in the literature. The number of tags can be estimated by 2.39 times of the number of collided slots [16], while it is also possible to use the two times of the number of collision slots or Chebyshev's inequality [14]. In addition, [21] suggests using a method with collision rate (i.e., collision estimator (CE)) or idle rate in a frame (zero estimator (ZE)). From our experimental results, which will be depicted and discussed in Section V-E, it is found that the estimation errors with the CE and ZE are relatively lower than others. Therefore, we use the following estimators:

$$\textit{Zero Estimator}: e^{-\hat{m}/f} = m_{idle}/f \tag{12}$$

$$\textit{Collision Estimator}: 1-\left(1+\hat{m}/f\right)\cdot e^{-\hat{m}/f} = m_{coll}/f \tag{13}$$

The estimator of the tag number, $\hat{m}$, is found by using the most approximate value to the ratio of right-hand, where the right-hand of (12) and (13) is the ratio of idle slot and collision slot occurred in the previous frame, respectively. From the analysis in [21], the normalized estimator variance (e.g., the estimation error) of ZE is less than or equal to CE for the load factor $m/f \le 0.77358$ and greater than CE for the load factor $m/f > 0.77358$. In other words, the estimation errors of ZE and CE cross at the load factor of 0.773581. In *OFSA*, the load factor is determined by γ, and then we obtain the relationship between γ and f^* by rearranging (11):

$$\gamma = \mathrm{e}\cdot w\left(-\ln\left(1-\frac{1}{f^*}\right)\cdot m - 1\right) + 1 \tag{14}$$

where $w(x)$ is the inverse function of Lambert's Omega function, and it is denoted as $w(x)=xe^x$. By substituting m to $0.773581f^*$ and taking f^* to infinity, we get the following result.

$$\lim_{f^*\to\infty} \gamma = \lim_{f^*\to\infty} \mathrm{e}\cdot w\left(-\ln\left(1-\frac{1}{f^*}\right)\cdot 0.77358 f^* - 1\right) + 1 \approx 0.50923 \tag{15}$$

Since f^* is strictly decreasing for $\gamma > 0$ (refer to Appendix B), we follow the rule for minimizing estimation errors:

- When γ is less than or equal to 0.509234, select ZE.
- When γ is greater than 0.509234, select CE.

4. Performance Analysis

In this section, we analyze the performance of time-optimal FSA (i.e., *OFSA*) and slot-optimal FSA. First of all, time-optimal FSA and slot-optimal FSA are defined.

Definition 1: Slot-optimal FSA is an adaptive FSA protocol, which minimizes the number of slots for identifying the given number of tags. In slot-optimal FSA, the optimization can be achieved by minimizing the expected slot delay in a frame.

Definition 2: Time-optimal FSA is an adaptive FSA protocol, which minimizes the duration time taken for identifying the given number of tags. In time-optimal FSA, the optimization can be achieved by minimizing the expected duration time between two identified tags in a frame.

Lemma 1: The optimal condition of slot-optimal FSA is $f^* = m$.

Proof: The successful transmission probability of a tag, s, is given by

$$s = \frac{m}{f}\left(1-\frac{1}{f}\right)^{-1}. \tag{16}$$

The first derivative of (16) for m is

$$\frac{\partial s}{\partial m} = \frac{1}{f}\left(1-\frac{1}{f}\right)^{m-1} \cdot \left(1+m\ln\left(1-\frac{1}{f}\right)\right). \tag{17}$$

By finding the condition when $\frac{\partial s}{\partial m} = 0$, we can find the optimal condition, which is given by $f = m$. The detailed proof of this lemma is given in [11].

Lemma 2: The expected slot delay of slot-optimal FSA for identifying m tags is e·m.

Proof: The maximal successful transmission probability, s^*, is given by (as also proved in [22]),

$$s^* \triangleq \lim_{m\to\infty} \Pr\left(X=1 \mid f=m\right) = \lim_{m\to\infty}\left(1-\frac{1}{m}\right)^{m-1} = \frac{1}{\mathrm{e}}. \tag{18}$$

Since the throughput and delay are in the relationship of reciprocal, the expected slot delay of identification of a tag, is e. Therefore, the expected slot delay when identifying m tags is e·m.

Lemma 3: The optimal condition of time-optimal FSA is $f^* = \left\lfloor \left\{1-\mathrm{e}^{-\left[1+W\left(\left(\gamma-1\right)/\mathrm{e}\right)\right]/m}\right\}^{-1} \right\rfloor$.[1]

Proof: The proof of this lemma follows the explanations in Section 3.

Lemma 4: The total identification delay in a tag collision arbitration protocol can be

[1] In Section 4, $(\cdot)^*$ and $(\cdot)^{**}$ denote the optimal condition in slot-optimal and time-optimal FSA, respectively.

represented by $\sum_{\chi \in \{succ, idle, coll\}} N_\chi \cdot T_\chi$ where N_χ and T_χ denote the total number and the duration of type-slots used to identify all tags, respectively.

Proof: If we only consider all slots consumed times until all tags are identified, slots are divided into success, idle, and collision slots. Therefore, the summation of the products of the total number of slots and the slot duration is the total identification time in a given collision arbitration protocol.

Lemma 5: The expected total identification delay of slot-optimal FSA is $m \cdot T_{succ} + \frac{p^*_{idle}}{p^*_{coll}} \cdot m \cdot T_{idle} + \frac{p^*_{coll}}{p^*_{succ}} \cdot m \cdot T_{coll} \approx m \cdot T_{succ} + m \cdot T_{idle} + (\mathrm{e}-2) \cdot m \cdot T_{coll}$.

Proof: According to Lemma 4, the total identification delay of slot-optimal FSA can be computed as

$$\sum_{\chi \in \{succ, idle, coll\}} N^{slot}_\chi \cdot T_\chi = N^{slot}_{succ} \cdot T_{succ} + N^{slot}_{idle} \cdot T_{idle} + N^{slot}_{coll} \cdot T_{coll} \tag{19}$$

Since slot-optimal FSA constantly maintains the maximum success probability s^*, the ratio of idle slots and the ratio of collision slots are asymtotically distributed as

$$p^*_{idle} \triangleq \lim_{m \to \infty} \Pr(X = 0 \mid f = m) = \lim_{m \to \infty} \left(1 - \frac{1}{m}\right)^m = \frac{1}{\mathrm{e}}, \tag{20}$$

$$p^*_{coll} \triangleq \lim_{m \to \infty} \Pr(X \geq 2 \mid f = m) = \lim_{m \to \infty} \left(1 - \frac{1}{m}\right) \cdot \left(1 - \frac{m}{m-1}\right)^m = 1 - \frac{2}{\mathrm{e}}. \tag{21}$$

On the other hand, the number of success slots, N^{slot}_{succ}, is m, and the numbers of idles and collision slots are given by $N^{slot}_{idle} = \mathrm{e} \cdot m \cdot p^*_{idle} = m$ and $N^{slot}_{coll} = \mathrm{e} \cdot m \cdot p^*_{coll} = (\mathrm{e} - 2) \cdot m$, respectively.

Lemma 6: If the probability of χ type slots in time-optimal FSA is p^{**}_χ, the expected total identification delay is approximated to $m \cdot T_{succ} + \frac{p^{**}_{idle}}{p^{**}_{succ}} \cdot m \cdot T_{idle} + \frac{p^{**}_{coll}}{p^{**}_{succ}} \cdot m \cdot T_{coll}$.

Proof: By Lemma 4 and the relationship between the throughput and delay, the expected slot delay is given by $\frac{1}{p^{**}_{succ}} \cdot m$. Using this, the expected total identification delay is calculated as $m \cdot T_{succ} + \frac{p^{**}_{idle}}{p^{**}_{succ}} \cdot m \cdot T_{idle} + \frac{p^{**}_{coll}}{p^{**}_{succ}} \cdot m \cdot T_{coll}$.

Theorem 1: For $0 < \gamma < 1$, the expected identification slot delay of time-optimal FSA is greater than or equal to that of slot-optimal FSA.

Proof: As shown in Lemma 6, the expected slot delay of time-optimal FSA is $\frac{1}{p^{**}_{succ}} \cdot m$. When $\gamma = 1$, we have $f^{**} = m$ from (11). Then we have $\frac{1}{p^{**}_{succ}} \cdot m = \mathrm{e} \cdot m$. f^{**} is strictly decreasing for $0 < \gamma < 1$, (Appendix B), and thus $f^{**} > m$ for $0 < \gamma < 1$. Consequently, $\frac{1}{p^{**}_{succ}} \cdot m > \mathrm{e} \cdot m$ for 0 <

$\gamma < 1$. Finally, the expected slot delay of time-optimal FSA is greater than or equal to that of slot-optimal FSA.

Theorem 2: For $0 < \gamma \leq 1$, the expected identification time delay of time-optimal FSA is less than or equal to that of slot-optimal FSA.

When γ is 1, $f^{**} = m$. Accordingly, the expected time delays of time-optimal FSA and slot-optimal FSA are equivalent. For the proof in case of $0 < \gamma < 1$, let us denote the total identification delays found in Lemma 5 and 6 as $\mathcal{D}_{SO}$ and $\mathcal{D}_{TO}$, respectively. Then the difference of total identification delay between the time-optimal FSA and slot-optimal FSA is:

$$\mathcal{D}_{TO} - \mathcal{D}_{SO} = \left(\frac{p_{idle}^{**}}{p_{succ}^{**}} - 1 \right) \cdot m \cdot \gamma \cdot T_{coll} + \left(\frac{p_{coll}^{**}}{p_{succ}^{**}} - (\mathrm{e} - 2) \right) \cdot m \cdot T_{coll} \tag{22}$$

and its derivative with respect to γ is computed as

$$\frac{\partial (\mathcal{D}_{TO} - \mathcal{D}_{SO})}{\partial \gamma} = T_{coll} \cdot \left(f^{**} - m - 1 - \frac{(f^{**} - 1) \cdot \mathrm{W}\left(\frac{\gamma - 1}{\mathrm{e}}\right)}{f^{**} \cdot m \cdot \left(1 + \mathrm{W}\left(\frac{\gamma - 1}{\mathrm{e}}\right)\right)} \right) \tag{23}$$

For $0 < \gamma < 1$, it is clarified that $\frac{\partial (\mathcal{D}_{TO} - \mathcal{D}_{SO})}{\partial \gamma} > 0$ with $m > 0$. It means that $\mathcal{D}_{TO} - \mathcal{D}_{SO}$ is increasing for $0 < \gamma < 1$, and thus $\mathcal{D}_{TO} - \mathcal{D}_{SO} < 0$ for $0 < \gamma < 1$. Therefore, for $0 < \gamma \leq 1$, the expected identification time delay of time-optimal FSA is less than or equal to that of slot-optimal FSA.

From Theorems 1 and 2, it can be found that time-optimal FSA (i.e., *OFSA*) shows longer identification slot delay than slot-optimal FSA when an idle slot has a shorter duration than a collision slot (i.e., *slot-time anomaly*). On the other hand, in terms of tag identification time, time-optimal FSA has shorter identification time. is the theorems In addition, if γ is 1 (i.e., the time delay of an idle slot and collision slot is identical), the identification time delays of time-optimal FSA and slot-optimal FSA are the same. In other words, *OFSA* behaves exactly in the same manner as slot-optimal FSA when the durations of idle and collision slots are the same. In conclusion, once a parameter γ is properly defined, the time-optimal FSA or *OFSA* can achieve the optimal performance in terms of time delay.

5. Performance Evaluation

We have evaluated *OFSA* performance in a comparative way with other protocols, considering various combinations of RFID standards and protocols. Throughout our evaluation study, tag identification time delay is regarded as a key performance metric. The performance of *OFSA* is compared against most Aloha-based protocols. We implemented our algorithm using C++ on the Microsoft Visual Studio .NET platform. The following two simulation environments are considered:

- Environment I: the environment referring to the air interface of ISO/IEC 18000-6 type A and B.
- Environment II: the environment referring to the EPC global Class-1 Generation-2 (ISO/IEC 18000-6 type C).

Table 1. Parameters used for performance evaluation.

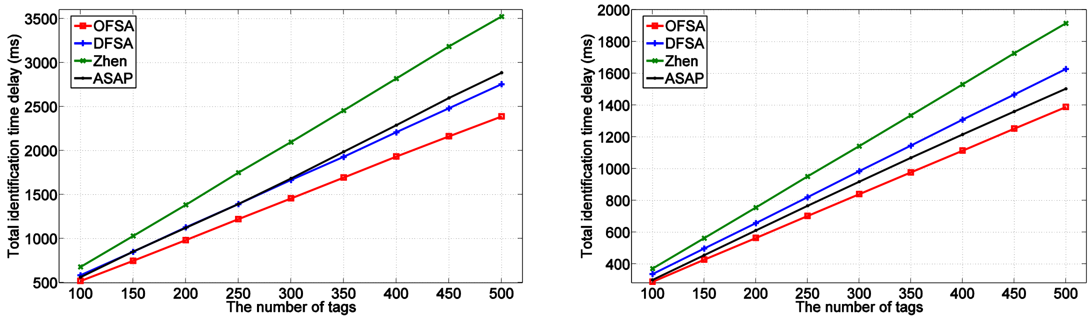
Environment classification		**Environment I**	**Environment II**
Referred standards		ISO/IEC 18000-6 type A/B	EPCglobal Class-1 Generation-2
Parameters		**Descriptions**	
Data transmission rate	Reader to tag	33 kbps	107 kbps
	Tag to reader	40 kbps	64 kbps
Tari (Reference time interval for reader-to-tag signal)		none	6.25 μs
Modulation	Modulation type	FM0	Miller subcarrier
	Number of subcarrier cycles per symbol	none	4
Slot duration	Success	2880 μs	2452.65 μs
	Idle	480 μs	37.5 μs
	Collision	2880 μs	1035.9 μs

In order to calculate the duration of each slot, we considered the transmission delay of messages between readers and tags by referring to the standards. However, in reality, the value of time delay may vary across the manufacturer/user setups of RFID readers. **Table 1** shows slot duration used in our simulation. Frames sized as powers of 2 is used for *OFSA* except for Section 5.1. Our simulation settings are based upon the message sizes of the RFID standards, and the message overheads caused by integer frame sizes are ignored. As we make all identified tags go into sleep (or quit) mode, all tags will answer only once during an identification process. All experimental results are averaged after 100 iterations with varying random seeds.

5.1 Comparison with FSA Protocols Using Integer Frame Sizes

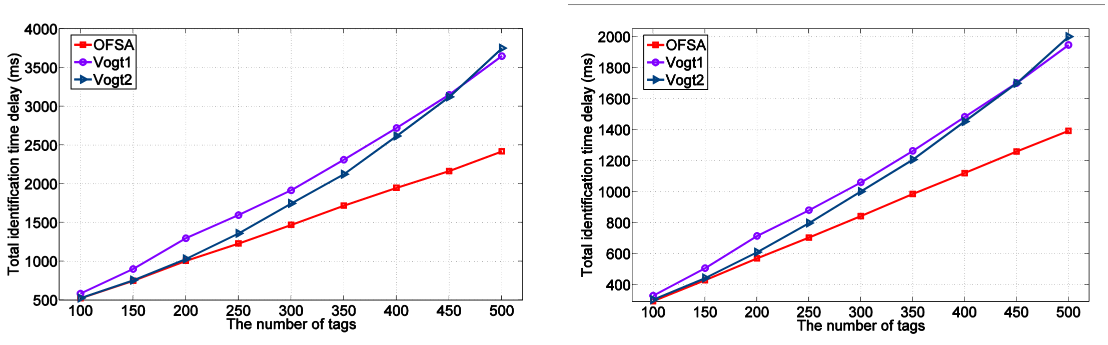
The adaptive FSA protocols, including Zhen [16], DFSA [11], and ASAP [19] which use integer frame sizes, are chosen for comparison. For a fair evaluation, ASAP, which was originally designed for its own virtual environment, is revised by us to use the slot duration parameters in Table I for its frame size daptation. *OFSA* follows the tag number estimator selection rule described in Section 3.2.2. **Fig. 2** plots the total identification time delay of *OFSA* and other protocols. Clearly, *OFSA* shows the shortest total identification time at all times. The performance difference between *OFSA* and other protocols manifests *OFSA*'s superiority in identification time optimization. Both DFSA and Zhen, which were developed based on slot-optimal FSA, reflect the performance degradation due to the *slot-time anomaly*. Considering the fact that ASAP uses the same tag number estimator (ZE) as *OFSA*, we can see this performance gap is made by their frame adaptation.[2] In its objective function, ASAP does not consider the time duration incurred by success slots as the overheads of identification. As a result, in the environment I, it ends up showing even worse identification delay than DFSA, a slot-optimal FSA protocol.

[2] The tag number estimator of ASAP acts simply as ZE except when idle slot count is zero. When a frame ended up resulting in no idle slot, it uses Vogt's estimator (=$2N_{coll}$)



(a) Total identification delay in environment I. (b) Total identification delay in environment II.

Fig. 2. Comparison with Aloha protocols using integer frame sizes.



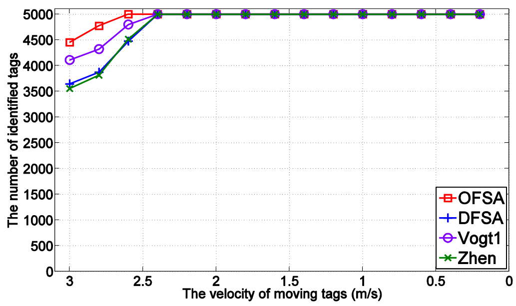
(a) Total identification delay in environment I. (b) Total identification delay in environment II.

Fig. 3. Comparison with Aloha protocols usingpower frame sizes.

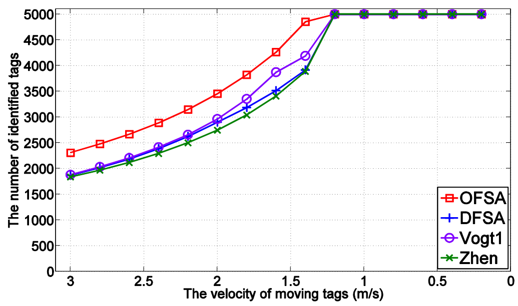
Since the frame adaptation in Zhen and DFSA is the same, their performance degradation is caused solely by their tag estimation errors. The detailed discussion of the effect of the tag estimation methods will be made later in the paper.

5.2 Comparison with FSA Protocols Using Power Frame Sizes

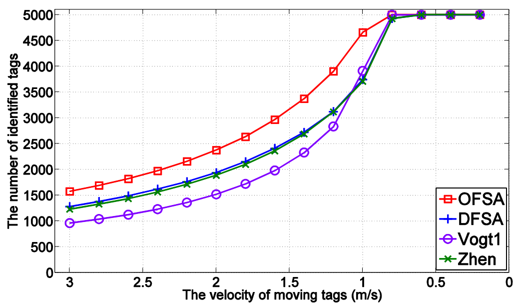
We chose the adaptive FSA protocol suggested in [14] for comparison which uses powers of 2 for frame size. The protocols in [14] are classified into two groups by which tag number estimator is used: (1) Vogt1 doubles the number of collision slots, and (2) Vogt2 selects the number of tags minimizing the distance from the vector with statistics on each slot. As illustrated in **Fig. 3**, although the eligible frame sizes are much less than in the case of integer frame sizes, *OFSA* shows comparable performance with the results shown in **Fig. 2**. Considering that the message overhead of integer frame sizes is not taken into account, power frame size *OFSA* will likely show better performance in reality. Furthermore, it has been seen that *OFSA* outperforms Vogt1, 2 both in **Fig. 3(a)** and **(b)**. These results are attributed to *OFSA*'s frame size adaptation scheme that achieves optimal performance virtually in any given environments, whereas the frame adaptation of Vogt series is designed specifically for I-CODE system.



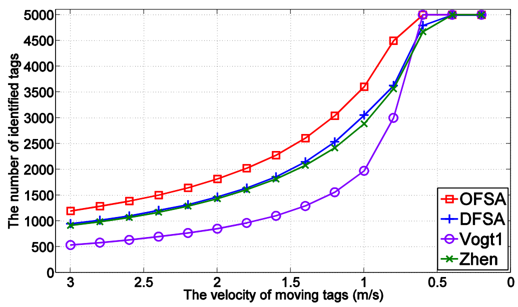
(a) Total identification delay when 5 tags per row.



(b) Total identification delay when 10 tags per row.

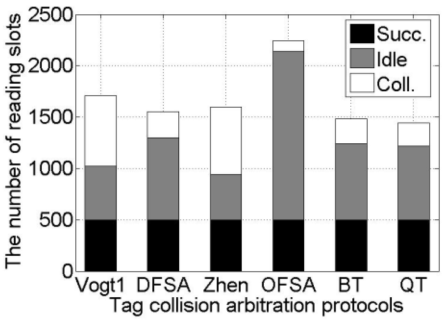


(c) Total identification delay when 15 tags per row.



(d) Total identification delay when 20 tags per row.

Fig. 4.Impact of tag mobility.



	Succ.	Idle	Coll.	Total
OFSA	500	1642.43	103.11	2245.54
Vogt1	500	524.53	682.25	1706.78
DFSA	500	798.97	252.11	1551.08
Zhen	500	439.79	657.04	1596.83
ASAP	500	1861.92	166.11	2528.03
BT	500	741.17	241.59	1482.76
QT	500	719.34	221.39	1440.73

Fig. 5. Proportion of success, idle, and collision slots when identifying 500 tags in environment I.

5.3 Impact of Tag Mobility

To reflect actual implementations, we also incorporate a tag mobility model to the environment I. The conveyor belt model is used as a tag mobility model, which may be viewed as a typical environment in many industrial systems. From 5 to 20 tags per row pass abreast the reader's identification area. The reader's identification range and the gap between rows are set to 3 meter and 0.1 meter, respectively. Simulation time is set to the time taken until all 5,000 tags passed through the reader's identification area. The protocols are evaluated in terms of the number of identified tags. DFSA, Vogt1, and Zhen are chosen for comparison. Only Vogt1 is set to use power frame sizes. In Fig. **Fig. 4(a)-(d)**, as many tags rush to the identification range, all protocols become rapidly degraded. In each figure, the protocols tend to miss logarithmically more tags as the speed of tags increases. Nevertheless, *OFSA* identifies more tags than the others under all the conditions being considered. In other words, *OFSA* may enable more reliable identification over the least number of readers or faster tag/product mobility. For example, let us assume that a conveyor system in a factory operates 12 hours per day, wherein 20 products are arranged in a row and move at the velocity of 1 m/s. In this scenario, the conveyor system with *OFSA* processes about 6,136,000 products (tags) on a daily basis, which outnumbers the system with the second-placed protocol, DFSA, by the margin of approximately 930,000 products. Considering the accumulation of the margin as the operation of systems continues, it is highly logical to conclude that *OFSA* will bring enormous productivity/cost-effectiveness to industrial systems.

5.4 Comparison in the Number of Used Slots

Fig. 5 confirms that DFSA, i.e., slot-optimized FSA, consumes obviously the smallest number of slots, whereas *OFSA* uses significantly more slots than DFSA. The result in **Fig. 5** reflects the *slot-time anomaly* effect and it allows us to determine which metric is practical. Many protocols to date consider only identification slot delay, Although the slot-optimal FSA protocols use less slots, they do not necessarily achieve time efficiency. The reason for this phenomenon comes from the fact that the duration of each slot is differentiated. Even if the duration of slots is all the same, *OFSA* will act just like a slot-optimal protocol; when $\gamma = 1$, Eq. (11) becomes $f^* = m$.

6. Conclusion and Future Work

In this paper, we proposed the optimum tag anti-collision protocol, *OFSA*, which achieves optimal tag identification delay. Tag identification time delay can serve as a good performance metric for adaptive FSA protocols, and our optimization scheme proved effective via a performance evaluation study. It is worth noting that *OFSA* does not require any modification to the existing RFID standards. *OFSA* can operate with the optimal time delay by simply changing a few parameters of RFID reader (not on tag side) in FSA standards. Therefore, *OFSA* could readily be used for applications sensitive to identification time delay. *OFSA* is being arranged to alternate the collision protocol in SK Telecom's reader SoC chip, which is currently being developed for not only for insdustrial but also personal use. After the chip is developed, it is expected that the protocol will be widely used for highly efficiency-driven applications such as industrial readers and mobile personal devices. In our future work, we plan to evaluate the performance of *OFSA* empirically by using RFID readers equipped with the chip.

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Appendix A
Proof of the Convexity

A.1 Convexity for *f*

Proof: We first review the convexity for f with the second derivative of the Eq. (8) as follows.

$$\frac{\partial^2 \mathcal{D}_{Tag|m,f}}{\partial f} = \frac{m-1}{f^3} \cdot \left(\frac{f}{f-1}\right)^{m+1}. \tag{24}$$

It allows us to know that $\frac{\partial \mathcal{D}_{Tag|m,f}}{\partial f} > 0$ for $f > 1$ and $m \geq 1$. Therefore, the objective function holds convexity with respect to f for $f > 1$ and $m \geq 1$.

A.2 Convexity for *m*

Proof: The convexity for m can also be examined by the second derivative:

$$\frac{\partial^2 \mathcal{D}_{Tag|m,f}}{\partial m} = 2f\left(1-\frac{1}{f}\right)^2 \cdot \left\{\frac{1}{m^3}+\ln\left(\left(1-\frac{1}{f}\right)\left(\frac{1}{m^2}+\frac{1}{m}\right)\right)\right\}. \quad (25)$$

Then, we see that $\frac{\partial^2 \mathcal{D}_{Tag|m,f}}{\partial m} > 0$ for $f > 1$ and $m \geq 1$. Therefore, the objective function also holds convexity with respect to m for $f > 1$ and $m \geq 1$.

Appendix B
Proof of Decreasing of f^* for γ

Proof: To investigate decreasing of f^*, we investigate the first derivative of Eq. (11). Let us substitute $\mathrm{e}^{\left(\mathrm{W}\left(\frac{1-\gamma}{\mathrm{e}}\right)-1\right)/m}$ and $\mathrm{W}\left(\frac{1-\gamma}{\mathrm{e}}\right)$ to α and β, respectively. Then the first derivative of Eq. (11) with respect to γ is denoted by

$$\frac{\partial f^*}{\partial \gamma} = -\frac{\alpha \cdot \beta}{(1-\alpha)^2 \cdot \beta \cdot m \cdot (\gamma-1)}. \quad (26)$$

In case where $m > 0$, we have $\alpha > 0$ and $\beta > 0$ for $0 < \gamma < 1$, and Eq. (26) holds the strict negativity. Accordingly, f^* is strictly decreasing for $0 < \gamma < 1$. And for $\gamma > 1$, f^* is strictly decreasing by the similar process. When $\gamma = 1$, the first derivative becomes indeterminate (0/0), however regarding it as 1, f^* is strictly decreasing for $\gamma > 0$.

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