A Time-Optimal Anti-collision Algorithm for FSA-Based RFID Systems

Donghwan Lee, Jihoon Choi, Wonjun Lee, Sangheon Pack, Ding-Zhu Du, and Sangjin Hong

With the introduction of the new generation RFID technology, EPCglobal Class-1 Generation-2, there is considerable interest in improving the performance of the framed slotted Aloha (FSA)-based tag collision arbitration protocol. We suggest a novel time-optimal anti-collision algorithm for the FSA protocol. Our performance evaluation demonstrates that our algorithm outperforms other tag collision arbitration schemes.

Keywords: Collision arbitration, RFID, tag anti-collision, frame slotted aloha, optimization.

I. Introduction

Tag anti-collision schemes have been proposed to ameliorate the efficiency of the RFID system. There are two approaches to achieve the given objective: a tree-based protocol and an Aloha-based one. These approaches have separately evolved using various techniques, such as the reuse of logged tagID [1] and dynamic frame adaptation [2]. However, after the EPCglobal Class-1 Generation-2 (Gen2) protocol [3] was ratified as the new UHF-band RFID standard, renewed interest in this area has been concentrated on improving the efficiency of the ALOHA-based one, that is, frame slotted Aloha (FSA).

The stochastic nature of FSA inevitably leads to collision and idle slots. Many initial studies on FSA [4], [5] regarded these slots as wasted and tried to minimize the unnecessary slots. Intriguingly, in real environments, we found that their assumption can lead to a misleading interpretation of the efficiency of FSA. As shown in Fig. 1, the duration of each slot varies in most RFID standards. Considering the disparity between slot durations, the so-called slot-optimal algorithm may not be effective in terms of identification time.

Meanwhile, only a couple of algorithms have considered efficient use of time as the primary performance metric. For example, there was experimentation on the anti-collision algorithm of [6], and it was adapted for the ISO/IEC 15693 (I-CODE) system [7]. However, as it considers only one standard, the same performance from other systems, including Gen2, is unlikely. The algorithm in [8] assumed a difference between slot durations, which when parameterized enabled its adaption to other FSA protocols. Nevertheless, since its modeling and evaluation was limited to only its own virtual environment, both its optimality and usability under verifiable conditions using legitimate RFID standards remain unproven.

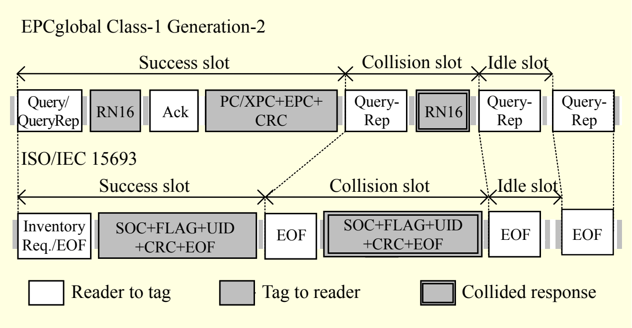

Fig. 1. Success, collision, and idle slots in EPCglobal Class-1 Generation-2 and ISO/IEC-15693 environment.

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Considering the problems mentioned above, in this letter, we derive a novel time-optimal anti-collision algorithm for FSA that emphasizes applicability for broad RFID standards.

II. Time-Optimal Frame Adaptation

In the FSA model, a reader informs tags of a frame size within which the tags randomly select their contending slot. In our analysis, the tag identification delay is defined as the average time duration between two successive identified tags. At the frame level, we can estimate the tag identification delay from the duration of a frame and the number of identified tags. Therefore, given m tags and frame size f, the tag identification delay in a frame is as

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

where τ and $p_{\mathrm{succ}|m,f}$ represent the expected duration of a frame and probability of successful identification in a slot, respectively. The probability of a given number of tags occupying a transmission slot is given by

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

Using (2), the probability a slot in a frame of size f is a success, an idle, or a collision slot is given by $p_{\mathrm{succ}|m,f} = Pr_{m,f}(X=1)$, $p_{\mathrm{idle}|m,f} = Pr_{m,f}(X=0)$, and $p_{\mathrm{coll}|m,f} = 1-Pr_{m,f}(X=1)-Pr_{m,f}(X=0)$, respectively. Then, the expected duration of a frame can be given by the summation of all expected delays in the frame:

$$\tau_{m,f} = FO + f \cdot p_{\mathrm{succ}|m,f} \cdot T_{\mathrm{succ}} + f \cdot p_{\mathrm{idle}|m,f} \cdot T_{\mathrm{idle}} + f \cdot p_{\mathrm{coll}|m,f} \cdot T_{\mathrm{coll}}, \tag{3}$$

where FO is the frame overhead, and T_{succ}, T_{idle}, and T_{coll} are the time duration of success, idle, and collision slots, respectively. By using (1) through (3), (1) can be rewritten as

$$\begin{aligned}\mathcal{D}_{\mathrm{Tag}|m,f} &= T_{\mathrm{succ}} + \frac{1}{m}\left(1-\frac{1}{f}\right)^{1-m} \cdot FO \\ &\quad + \left\{\frac{f}{m} \cdot \left[\left(\gamma-1\right)\left(1-\frac{1}{f}\right) + \left(1-\frac{1}{f}\right)^{1-m}\right] - 1\right\} \cdot T_{\mathrm{coll}},\end{aligned} \tag{4}$$

where γ is $T_{\mathrm{idle}} / T_{\mathrm{coll}}$.

Having observed the total identification time, we can optimize this objective by minimizing the tag identification delays in each frame until all tags are identified. For a given number of tags, the optimum frame size by objective function is determined by

$$\underset{f}{\operatorname{argmin}}\, \mathcal{D}_{\mathrm{Tag}|m,f}. \tag{5}$$

The objective function has the convexity property for f and m, (The proof is attained from the second derivative test: $\partial^2\mathcal{D}_{\mathrm{Tag}|m,f} / \partial f > 0$ and $\partial^2\mathcal{D}_{\mathrm{Tag}|m,f} / \partial m > 0$ for $f > 1$ and $m \geq 1$), that is, a local minimum found whereon the convex function is defined is necessarily the global minimum. To use this property without loss of generality, we assume that the frame size f is a positive integer and that there is no frame overhead. Then, we can differentiate the objective function for either f or m. As the inverse function of the derivative on f does not exist, we take the derivative of the objective function with respect to m:

$$\begin{aligned}\frac{\partial\mathcal{D}_{\mathrm{Tag}|m,f}}{\partial m} &= T_{\mathrm{coll}} \cdot \left[-\frac{1}{m^2}\left\{f\left(1-\frac{1}{f}\right)^{1-m} - \left(f-1\right)\left(\gamma-1\right)\right\}\right. \\ &\quad \left. -\frac{1}{m}\left\{\left(1-\frac{1}{f}\right)^{1-m} \cdot f \cdot \ln\left(1-\frac{1}{f}\right)\right\}\right].\end{aligned} \tag{6}$$

Then, by arranging $\partial\mathcal{D}_{\mathrm{Tag}|m,f} / \partial_m = 0$ with respect to f, we obtain the following relationship:

$$f^* = \left\lfloor \left\{1 - e^{-\left[1+W\left(\left(\gamma-1\right)/e\right)\right]/m}\right\}^{-1} \right\rfloor, \tag{7}$$

where $W(\cdot)$ denotes Lambert W function. Note that only m and γ determine the optimal frame size f. That is, we can easily customize the algorithm by adjusting only a few parameters. In general, FSA protocol-based RFID standards are restricted to using only powers of two for frame size: for example, the Gen2 standard prescribes the use of power-of-two values between 2^4 and 2^{12} for frame size. In this case, using the objective function (5) and introducing a constraint that bounds solution space f, we can make this problem a convex problem with a finite solution space: in Gen2, the nine power-of-two values from 2^4 to 2^{12}. Then, the optimum frame can be found by comparing the two power values adjacent to the integer solution from (7). For example, if an integer solution derived from (7) was 46 ($2^5 < 46 < 2^6$), then we can find the solution by comparing the two respective values from (4) with parameters given by $f=2^5$ and $f=2^6$.

This analytical solution is appropriate for RFID standards without a significant frame overhead, such as Gen2. On the other hand, this model may not be valid for environments with a large frame overhead, and we use the objective function (5), reconsidering the frame overhead. This problem can also be considered as a convex problem in a finite integer domain: The summation of convex functions results in a convex function. Using a bisection search on (5), we can determine the optimum frame size within $O(\log_2 n)$ time.

III. Tag Estimation

Because the exact number of tags is unknown until the identification process is finished, for an adaptation algorithm, it is essential to use a quality tag number estimator. For example, Vogt [6] was the first to suggest an estimator conceived from Chebyshev's inequality, which uses a value minimizing the distance between read results (the number of success, idle, and collision slots resulted in the previous frame) and their expectations. Cha and Kim [4] posited using the distance between only the number of collision slots and its expectation as a more accurate way to estimate the tag number collision estimator (CE). In addition, Kodialam and Nandagopal [9] analyzed the estimators in estimation performance and confirmed that according to conditions, that is, the physical parameters such as the value of gamma (time length ratio between collision slot and idle slot), using the CE, an idle estimator, or zero estimator (ZE) is the most eligible method for quantifying tags. Therefore, we use following estimators:

$$Zero\ Estimator: e^{-\hat{m}/f} = m_{\text{idle}}/f\ , \tag{8}$$

$$Collision\ Estimator: 1-\left(1+\hat{m}/f\right)\cdot e^{-\hat{m}/f} = m_{\text{coll}}/f\ . \tag{9}$$

The estimator of the tag number $\hat{m}$ is found by using the most approximate value to the ratio of the right-hand side, where the right-hand sides of (8) and (9) are the ratio of idle slot and collision slot occurred in the previous frame, respectively. From the analysis in [9], the normalized estimation variance, that is, the estimator error of ZE is less than or equal to CE for a load factor $m/f \leq 0.77358$. In our frame adaptation, the load factor is determined by γ, and then we obtain the relationship between γ and f^* by rearranging (7):

$$\gamma = e\cdot w\left(-\ln\left(1-\frac{1}{f^*}\right)\cdot m-1\right)+1, \tag{10}$$

where $w(x)$ is the inverse of Lambert W function $w(x) = x\cdot e^x$. By substituting m with $0.77358f^*$ and taking f^* to infinity, we get the following result:

$$\lim_{f^*\to\infty}\gamma = \lim_{f^*\to\infty} e\cdot w\left(-\ln\left(1-\frac{1}{f^*}\right)\cdot 0.77358f^*-1\right)+1 \approx 0.50923. \tag{11}$$

Since f^* is strictly decreasing for γ, we follow the rules for minimizing estimation errors: i) when $\gamma \leq 0.50923$, select ZE, and ii) when $\gamma > 0.50923$, select CE.

IV. Performance Evaluation

We have evaluated our algorithm in terms of the average identification time against other anti-collision algorithms: DFSA [4] (as a slot-optimal algorithm), Vogt [6], and ASAP [8]. We implemented all types of algorithms in an evaluation environment using a Visual C++ platform. The evaluation environment was divided into two according to the referred standard Gen2 or I-CODE, which respectively represent near-field and far-field RFID technology. Table 1 summarizes the parameters used in our simulation.

For a fair and thorough evaluation, we examined and tailored factors which can affect the evaluation results: i) ASAP, originally designed for a virtual protocol, was adapted for the slot duration parameters given by Table 1, ii) all algorithms are set to use powers of two for frame size, and DFSA was adapted to select the closest power value to its raw resulting frame size, and iii) all experimental results were averaged after 5,000 iterations with varying random seeds. Additionally, to prove the validity of our analysis, analytical values are calculated by taking the expectation of tag identification delay given the optimal condition (7) and an omniscient estimator, and we depicted the values along with simulation results.

Figures 2(a) and (b) plot the average identification delay to identify one tag in the Gen2 and I-CODE environment. In the Gen2 environment, the time-optimal algorithm outpaces the other algorithms in tag identification delay, showing close agreement with the analytical results as the tag number is

Table 1. Parameters used for performance evaluation.

a) Parameters for EPCglobal Class-1 Gen2.

<table>
<tr><th>Parameters</th><th>Values</th><th colspan="2">Parameters</th><th>Values</th></tr>
<tr><td>Data coding</td><td>Miller subcarrier modulation</td><td colspan="2">No. of subcarrier cycles per symbol</td><td>4</td></tr>
<tr><td>R->T rate</td><td>107 kbps</td><td colspan="2">R->T preamble</td><td>67.19 µs</td></tr>
<tr><td>T->R rate</td><td>64 kbps</td><td colspan="2">T->R preamble</td><td>62.5 µs</td></tr>
<tr><td>Backscatter link frequency (BLF)</td><td>256 kbps</td><td colspan="2">TRcal (T->R calibration symbol)</td><td>31.25 µs</td></tr>
<tr><td>Tari (reference time interval)</td><td>6.25 µs</td><td colspan="2">RTcal (R->T calibration symbol)</td><td>17.19 µs</td></tr>
<tr><td><i>FO</i></td><td>206 µs</td><td colspan="2"><i>DR</i> (divide ratio)</td><td>8</td></tr>
<tr><td>T_{succ}</td><td>1953.9 µs</td><td rowspan="3">Link timing</td><td>T_1</td><td>52.08 µs</td></tr>
<tr><td>T_{idle}</td><td>153.75 µs</td><td>T_2</td><td>15.625 µs</td></tr>
<tr><td>T_{coll}</td><td>467.97 µs</td><td>T_3</td><td>10 µs</td></tr>
</table>

b) Parameters for ISO/IEC 15693 (I-CODE).

<table>
<tr><th>Parameters</th><th>Values</th><th colspan="2">Parameters</th><th>Values</th></tr>
<tr><td>Data coding</td><td>Pulse position modulation (1/4)</td><td colspan="2">EOF type</td><td>100%-modulated</td></tr>
<tr><td>R->T rate</td><td rowspan="2">26.48 kbps</td><td colspan="2"><i>FO</i></td><td>4231.84 µs</td></tr>
<tr><td>T->R rate</td><td colspan="2">SOF duration</td><td>75.5 µs</td></tr>
<tr><td>T_{succ}</td><td>3,950.97 µs</td><td rowspan="3">Link timing</td><td>T_1</td><td>320.9 µs</td></tr>
<tr><td>T_{idle}</td><td>398.8 µs</td><td>T_2</td><td>309.2 µs</td></tr>
<tr><td>T_{coll}</td><td>3,950.97 µs</td><td>T_3</td><td>398.8 µs</td></tr>
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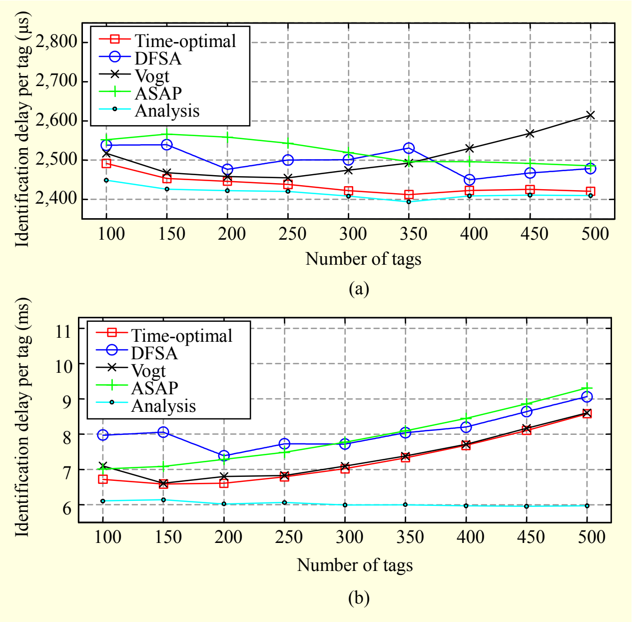

Fig. 2. Performance comparison between anti-collision algorithms (a) in Gen2 environment and (b) in I-CODE environment.

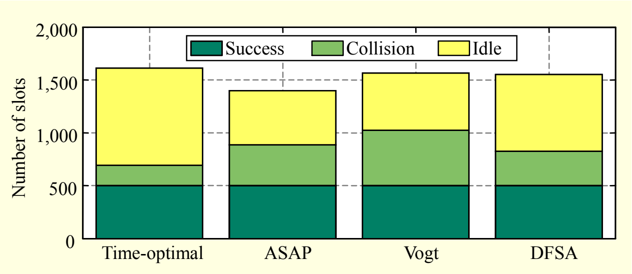

Fig. 3. Proportion of success, idle, and collision slots during identification of 500 tags in Gen2 environment.

increased. In the I-CODE environment, our algorithm still achieves the shortest tag identification time. In this environment, however, we observe performance gaps between the time-optimal and the analytical values as the tag number is increased. Our analysis on this phenomenon has found that the gaps come from the accumulated estimation error related to strong limitation of frame size (maximum 2^8) in the I-CODE environment. Vogt, the algorithm based on the actual experiment, is closely behind the time-optimal algorithm in Fig. 2(b), but as shown in Fig. 2(a), it did not take into account the adaptability to the environments other than I-CODE. Likewise, the time-optimal algorithm outperforms ASAP in both evaluations. Our objective function uses the same metric, that is, the average identification delay used in the evaluation, whereas ASAP tries to minimize the ratio of time consumed by success slots to time wasted by other slots. Furthermore, as ASAP does not consider the frame overhead, it can deteriorate more in some RFID environments with large overheads, such as I-CODE.

Figure 3 clarifies the difference between the time-optimal and other algorithms via slot statistics. While the algorithm pursuing slot-optimality, that is, DFSA, shows the lowest slot consumption, the time-optimal algorithm consumes relatively more slots than other algorithms. In particular, it consumes the highest number of idle slots and fewest collision slots of all algorithms. This means that our algorithm finds the best trade-off in terms of time efficiency by exploiting a large frame size with many idle slots. Although our evaluation has been conducted in only two major environments, it is obvious that our scheme will be equally competitive for most RFID standards based on FSA-like protocols.

V. Conclusion

In this letter, we proposed a time-optimal anti-collision algorithm for FSA protocols. The performance evaluation proved that our algorithm achieves improved identification time delay. In addition, our scheme, with minimal revision, can be immediately applied to all existing RFID standards using the FSA protocol. Due to such features, our scheme has been selected as one of the core algorithms for SK Telecom's reader SoC chip products, which we expect will enable the creation of the first commercialized converged RFID/cellular networks.

References

[1] J. Myung et al., "Tag-Splitting: Adaptive Collision Arbitration Protocols for RFID Tag Identification," *IEEE Trans. Parallel Distrib. Syst.*, vol. 18, no. 6, June 2007, pp. 763-775.

[2] F.C. Schoute, "Dynamic Frame Length Aloha," *IEEE Trans. Commun.*, vol. 31, no. 4, Apr. 1983, pp. 565-568.

[3] EPCglobal Gen2, *EPC Radio-Frequency Identity Protocols Class-1 Generation-2 UHF RFID Protocol for Communications at 860 MHz - 960 MHz*, EPCglobal, ver.1.2.0, Oct. 2008.

[4] J. Cha and J. Kim, "Novel Anti-collision Algorithms for Fast Object Identification in RFID System," *Proc. IEEE ICPADS*, 2005, p. 63.

[5] B. Zhen, M. Kobayashi, and M. Shimizu, "Framed Aloha for Multiple RFID Objects Identification," *IEICE Trans. Commun.*, vol. 88-B, Oct. 2005, pp. 991-999.

[6] H. Vogt, "Efficient Object Identification with Passive RFID Tags," *Proc. Pervasive*, 2002, p. 98.

[7] ISO/IEC 15693, *Identification cards - Contactless Integrated Circuit(s) Cards - Vicinity Cards - Part 3: Anticollision and Transmission Protocol*, ISO/IEC, ver.1.0, Nov. 1999.

[8] G. Khandelwal et al., "ASAP: A MAC Protocol for Dense and Time-Constrained RFID Systems," *Proc. IEEE ICC*, 2006, p. 4028.

[9] M. Kodialam and T. Nandagopal, "Fast and Reliable Estimation Schemes in RFID Systems," *Proc. ACM MOBICOM*, 2006, p. 322.