Tag Anti-Collision Algorithms in Passive and Semi-passive RFID Systems

Part II : CHI Algorithm and Hybrid Q Algorithm by using Chebyshev's Inequality

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ABSTRACT

Both EPCglobal Generation-2 (Gen2) for passive RFID systems and Intelleflex for semi-passive RFID systems use probabilistic slotted ALOHA with Q algorithm, which is a kind of dynamic framed slotted ALOHA (DFSA), as the tag anti-collision algorithm. A better tag anti-collision algorithm can reduce collisions so as to increase the efficiency of tag identification. In this paper, we introduce and analyze the estimation methods of the number of slots and tags for DFSA. To increase the efficiency of tag identification, we propose two new tag anti-collision algorithms, which are Chebyshev's inequality (CHI) algorithm and hybrid Q algorithm, and compare them with the conventional Q algorithm and adaptive adjustable framed Q (AAFQ) algorithm, which is mentioned in Part I. The simulation results show that AAFQ performs the best in Gen2 scenario. However, in Intelleflex scenario the proposed hybrid Q algorithm is the best. That is, hybrid Q provides the minimum identification time, shows the more consistent collision ratio, and maximizes throughput and system efficiency in Intelleflex scenario.

Key Words : RFID, Tag Anti-collision, Gen2, Intelleflex, Passive, Semi-passive

Ⅰ. Introduction

Radio frequency identification (RFID) system is a contactless automatic identification system, which comprises interrogators, also known as readers, and tags, also known as labels[1]. A reader can identify a tag by its unique ID number and obtain the information stored in the tag. When multiple tags respond to the reader at the same time, a tag collision occurs and the reader fails to identify any tag. A good tag anti-collision algorithm can reduce collisions so as to increase the efficiency of identification.

Two widely used tag anti-collision algorithms in RFID systems are binary tree algorithm and ALOHA algorithm[2]. Binary tree algorithm splits tags into two subsets when there is a collision, then divides and conquers every subset separately. On the other hand, ALOHA algorithm decreases the probability of collision by scheduling the responses of tags[3]. Both of them are based on TDMA.

For ALOHA algorithm, there are various kinds. The simplest version of ALOHA algorithm is pure ALOHA. When a tag reaches the interrogation area of a reader, the tag will transmit the data immediately. This algorithm has a high probability of collision[2], [4]. An improved algorithm is slotted ALOHA. In this algorithm, time is divided into slots, and tags can only respond at the beginning of a time slot. As a consequence, the rate of collision can be reduced by half[4], [5]. However, due to the limitation of the number of

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slots, this algorithm is usually used in the case that there are a few tags in the interrogation zone. Framed slotted ALOHA (FSA) algorithm can solve this problem. In this algorithm, time is divided into frames and every frame consists of several slots. However, this FSA uses a fixed frame size and does not change the frame size during the process of tag identification, which is simple, but not efficient for tag identification[2]. Dynamic framed slotted ALOHA (DFSA) algorithm can change the frame size to increase the efficiency of tag identification, and there exist several ways to modify the frame size[6]-[8].

Both EPCglobal Class-1 Generation-2 for passive RFID systems and Intelleflex for semi-passive RFID systems use probabilistic slotted ALOHA with Q algorithm, which is a kind of DFSA, as a tag anti-collision algorithm[1], [9]. The analysis of probabilistic slotted ALOHA with Q algorithm is provided in Part I[10]. In this paper, we propose a new tag anti-collision algorithm based on Chebyshev's inequality and combine this algorithm with AAFQ algorithm which is proposed in Part I[10]. The proposed algorithms use Chebyshev's inequality to estimate the number of tags, which is more accurate than the conventional Q algorithm, so as to increase the efficiency of tag identification.

The remaining part of this paper is organized as follows. Section II introduces and compares slot estimation methods and tag estimation methods for DFSA. In section III, we propose new tag anti-collision algorithms, and section IV provides the performance verification for the conventional Q algorithm and the proposed algorithms both for passive RFID systems and semi-passive RFID systems. Finally, section V draws conclusions.

Ⅱ. Dynamic Framed Slotted ALOHA

Dynamic Framed Slotted ALOHA (DFSA) changes the frame size dynamically. To set the appropriate length of frame, slot estimation is required to estimate the optimal frame size. For slot estimation, we need to know the number of tags. So both slot and tag estimation methods are essential in DFSA.

2.1 Slot Estimation Methods

There are two methods to estimate the optimal number of slots. The first one is based on the minimization of identification time, and the second one considers maximizing the system throughput. Both of them draw the same conclusion that the optimal frame size is equal to the number of tags[7]:

$$L_{\text{optimal}} = n\,. \tag{1}$$

2.2 Tag Estimation Methods

According to (1), the number of slots is equal to the number of tags. Therefore, in order to estimate the number of slots, we should estimate the number of tags first, using one of the methods below.

2.2.1 Lower Bound

The first estimation method is obtained through the observation that a collision involves at least two different tags[6]. Therefore, a lower bound on the number n of tags can be obtained by the following simple estimation equation:

$$n_{\text{LowerBound}} = 2\times(\text{Number of Collided Slots})\,. \tag{2}$$

2.2.2 Maximum Throughput

The posteriori expectation on the number of tags that choose one time slot simultaneously is equal to 2.39[11]. Using this posteriori expected value, a system can reach the maximum throughput[6]. Therefore, the number n of tags can be calculated by:

$$n_{\text{MaximumThroughput}} = 2.39\times(\text{Number of Collided Slots})\,. \tag{3}$$

2.2.3 Collision Ratio

Given N slots and n tags, the number r of tags in one slot is binomially distributed with parameters n and 1/N[6]:

$$B_{n,\frac{1}{N}}(r) = \binom{n}{r}\left(\frac{1}{N}\right)^{r}\left(1-\frac{1}{N}\right)^{n-r}. \tag{4}$$

The number r of tags in a particular slot is called the occupancy number of the slot, and the expected value $a_r^{N,\,n}$ of the number of slots with occupancy number r[6] is derived as

$$a_r^{N,n} = NB_{n,\frac{1}{N}}(r) = N\binom{n}{r}\left(\frac{1}{N}\right)^r\left(1-\frac{1}{N}\right)^{n-r}. \quad (5)$$

Consequently the expected value $a_0^{N,n}$ of the number of empty slots is given by

$$a_0^{N,n} = NB_{n,\frac{1}{N}}(0) = N\binom{n}{0}\left(\frac{1}{N}\right)^0\left(1-\frac{1}{N}\right)^n = N\left(1-\frac{1}{N}\right)^n, \quad (6)$$

and the expected value $a_1^{N,n}$ of the number of successful slots is given by

$$a_1^{N,n} = NB_{n,\frac{1}{N}}(1) = N\binom{n}{1}\left(\frac{1}{N}\right)^1\left(1-\frac{1}{N}\right)^{n-1} = n\left(1-\frac{1}{N}\right)^{n-1}. \quad (7)$$

Then the expected value $a_k^{N,n}$ of the number of collided slots becomes as

$$a_k^{N,n} = NB_{n,\frac{1}{N}}(k) = N - a_0^{N,n} - a_1^{N,n}, \quad k \ge 2. \quad (8)$$

Consequently, the collision ratio can be derived as

$$\begin{aligned} C_{ratio} &= 1 - P_{succ} - P_{empty} \\ &= 1 - B_{n,\frac{1}{N}}(1) - B_{n,\frac{1}{N}}(0) \\ &= 1 - \binom{n}{1}\left(\frac{1}{N}\right)^1\left(1-\frac{1}{N}\right)^{n-1} - \binom{n}{0}\left(\frac{1}{N}\right)^0\left(1-\frac{1}{N}\right)^{n-0} \\ &= 1 - \left(1-\frac{1}{N}\right)^n\left(1+\frac{n}{N-1}\right), \end{aligned} \quad (9)$$

where P_{succ} is the probability of successful slots and P_{empty} is the probability of empty slots.

After one frame, we have the information of frame size N and collision ratio C_{ratio}, so the number n of tags can be calculated by using (9).

2.2.4 Chebyshev's Inequality

This method is based on the fact that the outcome of a random experiment is most likely somewhere near the expected value[6]. Thus an alternative estimation function uses the distance between the read result c and the expected value vector to determine the value of n for which the distance becomes minimal. We denote this estimation function by ξ as

$$\xi(N, c_0, c_1, c_k) = \min_n \left| \begin{pmatrix} a_0^{N,n} \\ a_1^{N,n} \\ a_{\ge 2}^{N,n} \end{pmatrix} - \begin{pmatrix} c_0 \\ c_1 \\ c_k \end{pmatrix} \right|, \quad (10)$$

where $a_0^{N,n}$, $a_1^{N,n}$, and $a_{\ge 2}^{N,n}$ are given by (6) ~ (8).

Now, we compare the performance of these four tag estimation methods in Fig. 1 to 3. Fig. 1 compares the total number of slots for tag identification. In these four methods, Chebyshev's inequality using (10) costs the minimum number of slots. The estimation errors

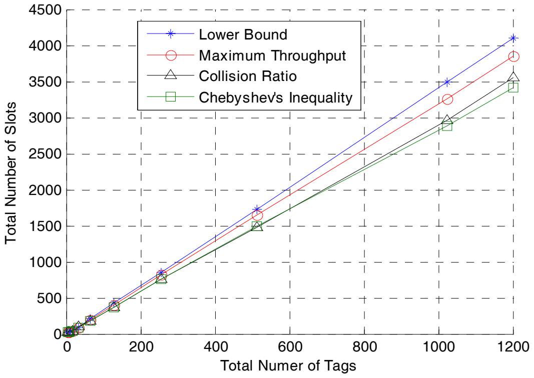

Fig. 1. Total number of slots for tag identification by four tag estimation methods

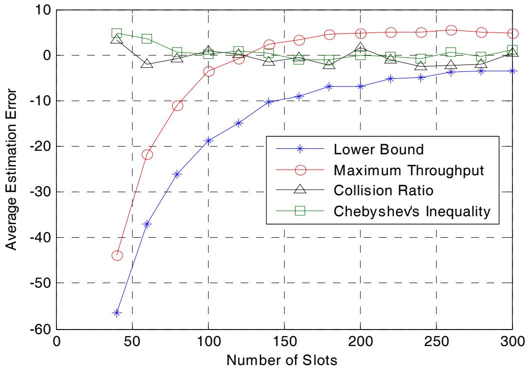

Fig. 2. Estimation error for the case of 128 tags

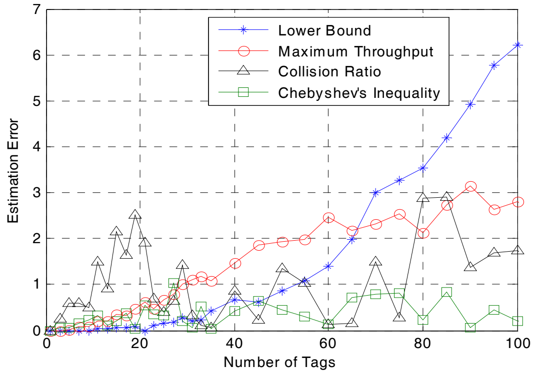

Fig. 3. Estimation error for the case of a 128-slot-long frame

of these four methods, which are defined as the difference between the estimated number of tags and the real number of tags, are given in Fig. 2 and 3. First, we fix the number of tags and vary the number of slots, which is equal to the initial frame size. In Fig. 2, we can observe that the methods of Chebyshev's inequality and collision ratio have less average estimation errors than the methods of lower bound and maximum throughput. In Fig. 3, we set the number of slots fixed and the number of tags varying. In this case, Chebyshev's inequality outperforms the other three methods. That is, Chebyshev's inequality is the best among the four tag estimation methods.

Ⅲ. Proposed Anti-collision Algorithms based on Chebyshev's Inequality

Probabilistic slotted ALOHA with Q algorithm uses Query command, which includes a parameter Q, to set the frame size, and the corresponding frame size is equal to 2^Q. After a frame, QueryAdjust command is transmitted from reader to tag to increase or decrease the Q value by 1 in Gen2 scenario. Consequently, the frame size is doubled or divided by 2. Because the frame size must be the multiples of 2, it may not be the optimal length of the frame according to (1). Therefore, we can use other more accurate tag estimation methods to replace Q algorithm in Gen2 scenario. On the other hand, Intelleflex uses the same Q algorithm as that used in Gen2 except that Query command is used to change the Q value[9]. Therefore, the proposed algorithm can be used for both Gen2 and Intelleflex.

3.1 Chebyshev's Inequality (CHI) Algorithm

Section II has introduced four methods to estimate the number of tags, which are the methods of lower bound, maximum throughput, collision ratio, and Chebyshev's inequality, and we verified that the method of Chebyshev's inequality (10) gives the most accurate estimation for the number of tags.

Now, we propose Chebyshev's inequality (CHI) algorithm to estimate the optimal length of frame, which is set to the size of the following frame, instead of Q algorithm used in Gen2 and Intelleflex. Fig. 4 shows the implementation of probabilistic slotted ALOHA with Q algorithm in Gen2. The detailed procedure of this implementation is explained in Part I[10]. At the end of a frame, QueryAdjust command is transmitted to modify the frame size. However, in the proposed CHI algorithm, QueryAdjust command is replaced by using Chebyshev's inequality to set the size of the following frame shown in Fig. 5, where the proposed

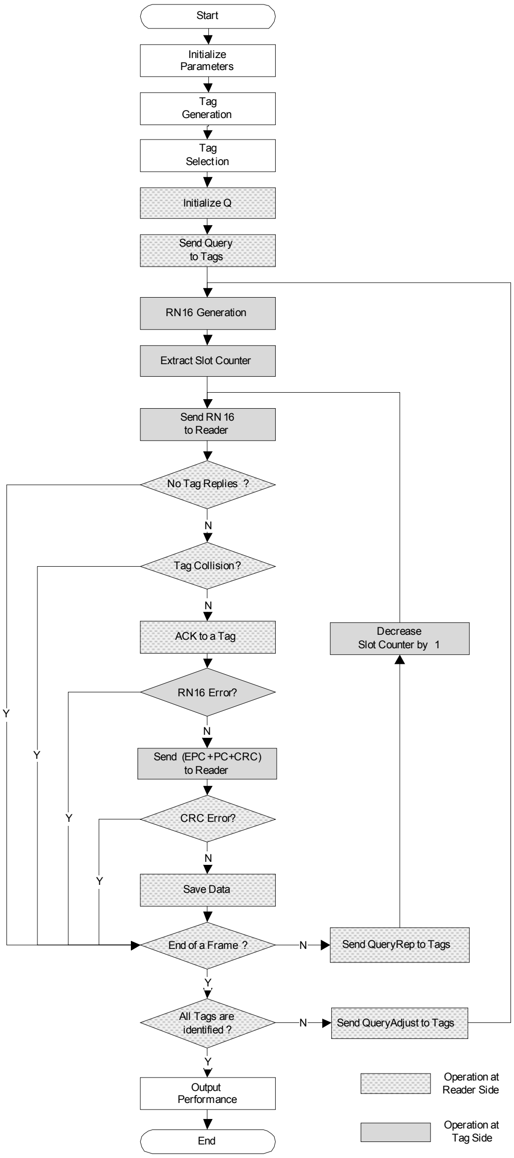

Fig. 4. Implementation of probabilistic slotted ALOHA in Gen2

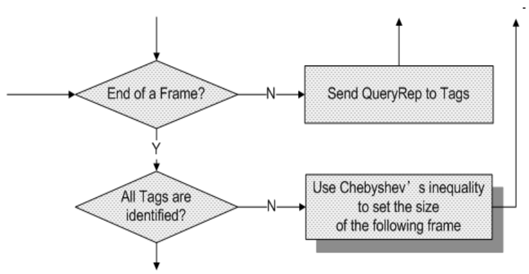

Fig. 5. Flow chart of CHI algorithm

part is denoted by a shadowed block. Because the proposed CHI algorithm can estimate the number of tags accurately and get an optimal frame size, it can improve the performance of tag identification compared with the conventional Q algorithm.

3.2 Hybrid Q Algorithm

Adaptive adjustable framed Q (AAFQ) algorithm is proposed in Part I[10]. This algorithm uses two threshold values Th_{coll} and Th_{emp}, compares these two threshold values with the continuous numbers of the collided or empty slots respectively, and modifies the frame size dynamically. By combining the ideas of AAFQ and CHI, we propose hybrid Q algorithm, which uses Chebyshev's inequality to estimate and set the frame size at the beginning of a frame, while during a frame the threshold values of Th_{coll} and Th_{emp} are used to decide to increase or decrease the current frame size by comparing them with the continuous numbers of collided and empty slots, respectively. Fig. 6 shows the flow chart of hybrid Q algorithm, where the proposed parts are denoted by shadowed blocks. The detailed description of hybrid Q algorithm is provided in Fig. 7.

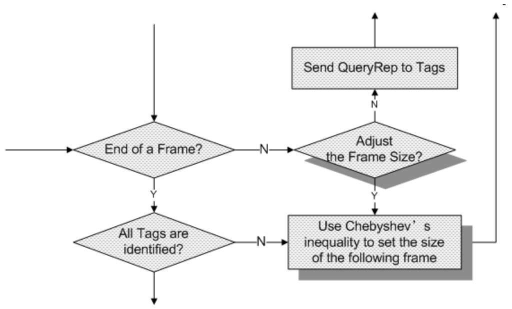

Fig. 6. Flow chart of Hybrid Q algorithm

```
Reader sends Query.
for inventory procedure
    Every tag generates RN16 & slot counter.
    for current frame
        If slot counter == 0
            Tag replies its RN16.
        end
        If a single tag replies
            Reader sends ACK with RN16.
            If RN16 received by tag == RN16 saved in tag
                Tag sends EPC to reader.
            end
            Reader sends QueryRep.
        else if multiple tags reply
            If number of continuous collided slots > $Th_{coll}$
                Reader sendsQueryAdjust.
                $Q = Q + 1$
                $Th_{emp} = Th_{emp} + 1$
                $Th_{coll} = Th_{coll} + 1$
            else
                Reader sendsQueryRep.
            end
        else if no tag replies
            If number of continuous empty slots > $Th_{emp}$
                Reader sendsQueryAdjust.
                $Q = Q - 1$
                $Th_{emp} = Th_{emp} - 1$
                $Th_{coll} = Th_{coll} - 1$
            else
                Reader sendsQueryRep.
            end
        end
        If tag receives QueryRep
            slot counter = slot counter - 1
        end
    end
    Use Chebyshev's inequality to set the size of the following frame.
end
```

Fig. 7. Hybrid Q algorithm

Ⅳ. Simulation Results and Performance Verification

According to the previous analysis and design, we do simulation for the proposed CHI and hybrid Q algorithms, and compare them with the conventional Q algorithm and AAFQ algorithm, which is proposed in Part I[10], at the aspects of identification time, throughput, system efficiency, and collision ratio in both Gen2 and Intelleflex scenarios. These performance indexes are defined in Part I[10].

4.1 Performance in Gen2 Scenario

The simulation parameters for Gen2 scenario are shown in Table 1, which are chosen based on the Gen2 specification. Besides, to adaptively adjust the

Table 1. Simulation parameters for Gen2 scenario[12]

Parameters	Descriptions	Values in Specification	Values in Simulation
Tari	Reference time interval for a data-0 in Interrogator-to-Tag signaling	6.25 µs, 12.5 µs, or 25 µs	12.5 µs
DR	Divide Ratio	64/3 or 8	8
RTcal	Interrogator-to-Tag calibration	2.5 Tari ≤ RTcal ≤ 3.0 Tari	3 Tari = 37.5 µs
TRcal	Tag-to-Interrogator calibration RTcal ≤ TRcal ≤ 3 RTcal	17.2 µs ≤ TRcal ≤ 200 µs, if DR = 8	2 RTcal= 75 µs
LF	Link frequency	LF = DR/TRcal	107 kHz
T_{pri}	Link pulse-repetition interval	T_{pri} = 1/LF	9.375 µs
T_1	Time from Interrogator transmission to Tag response	MAX (RTcal, 10 T_{pri})	10 T_{pri} = 93.75 µs
T_2	Time from Tag response to Interrogator transmission	3.0 T_{pri} ≤ T_2 ≤ 20.0 T_{pri}	10 T_{pri} = 93.75 µs
T_3	Time an Interrogator waits, after T_1, before it issues another command	0.0 T_{pri}	0 µs
T_4	Minimum time between Interrogator commands	2.0 RTcal	75 µs
T=>R Data Rate	Tag-to-Interrogator link data rate	LF, if FM0 modulation	LF = 107 kbps
T=>R Preamble	Precede the responses from tags.	6 or 18 clocks, if FM0 modulation	168.75 µs
R=>T Preamble	Precede a Query command and denote the start of an inventory round.	12.5 + Tari + RTcal + TRcal	137.5 µs
R=>T Frame-sync	Precede all commands except Query.	12.5 + Tari + RTcal	62.5 µs

threshold values of Th_{coll} and Th_{emp} according to the varying frame size, both Th_{coll} and Th_{emp} are set to be equal to the Q value in AAFQ and hybrid Q algorithms.

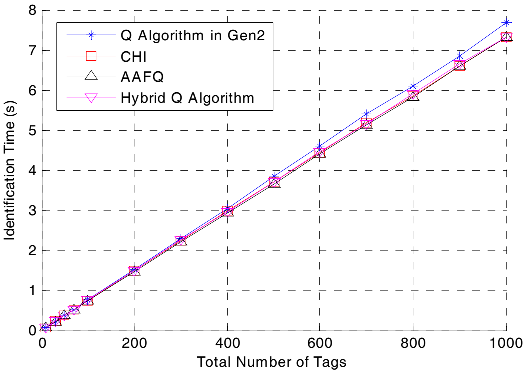

Fig. 8. Identification time of Q algorithm and the proposed algorithms in Gen2 scenario

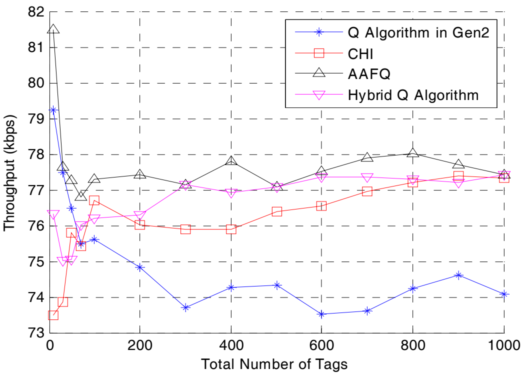

Fig. 9. Throughput of Q algorithm and the proposed algorithms in Gen2 scenario

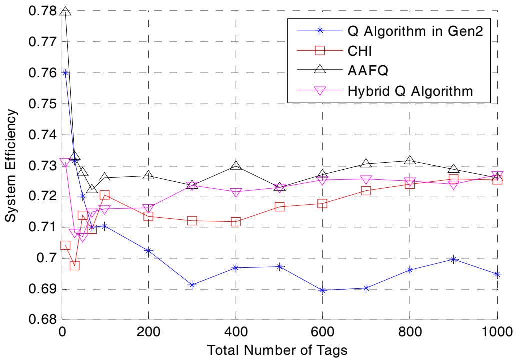

Fig. 10. System efficiency of Q algorithm and the proposed algorithms in Gen2 scenario

Comparison of algorithms for each performance index is shown in Fig. 8 to 11. Fig. 8 shows the identification time of the conventional Q algorithm, AAFQ, CHI, and hybrid Q algorithms. We can observe that all the proposed algorithms reduce the identification time compared with Q algorithm used in Gen2. However, there are no big differences among AAFQ, CHI, and hybrid Q algorithms in reducing identification time. Fig. 9 and 10 describe throughput and system efficiency, respectively. We can observe that the proposed CHI and hybrid Q algorithms outperform Q algorithm, and AAFQ algorithm shows the best

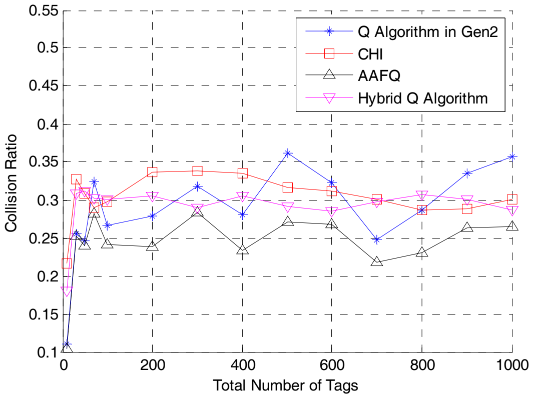

Fig. 11. Collision ratio of Q algorithm and the proposed algorithms in Gen2 scenario

throughput and system efficiency. At last, the comparison for collision ratio is shown in Fig. 11, in which CHI and hybrid Q algorithms show the more consistent collision ratio, regarding the total number of tags, than that of Q algorithm, and the collision ratios of AAFQ outperform the other three algorithms.

Based on the above discussion, we conclude that AAFQ shows the best performance among all the conventional and proposed anti-collision algorithms in Gen2 scenario. That is, AAFQ algorithm provides the minimum identification time and collision ratio and maximizes throughput and system efficiency.

4.2 Performance in Intelleflex Scenario

Intelleflex for semi-passive RFID systems also uses probabilistic slotted ALOHA with Q algorithm as the tag anti-collision algorithm. Compared with Gen2, Intelleflex uses Query command, instead of QueryAdjust command, to change the frame size. But this will not affect the anti-collision algorithm itself. Therefore, the same proposed CHI algorithm and hybrid Q algorithm for Gen2 can also be applied in Intelleflex scenario.

Table 2. Simulation parameters for Intelleflex scenario.

	Forward Link (R=>T)	Reverse Link (T=>R)
Data Rate	8 kbps	32 kbps
Data Encoding	Manchester	FSK
Preamble Duration	7.5 clocks = 937.5 ㎲	6 clocks = 187.5 ㎲

Compared with Gen2, the preambles used in Intelleflex are much longer for both forward and reverse link. The parameters for data rate, data encoding, and preamble duration used in our simulator are shown in Table 2, which come from the specification of Intelleflex. Other parameters used in the simulator are the same to those in Gen2.

The simulation results in intelleflex senario are shown in Fig. 12 to 17. Fig. 12 shows that the identification time in Intelleflex scenario is much longer than that in Gen2 for both conventional Q algorithm and the proposed algorithms. For throughput and efficiency, Gen2 also outperforms Intelleflex as in Fig. 13 and 15. The reason is that Intelleflex uses the much longer preambles than Gen2. However, the collision

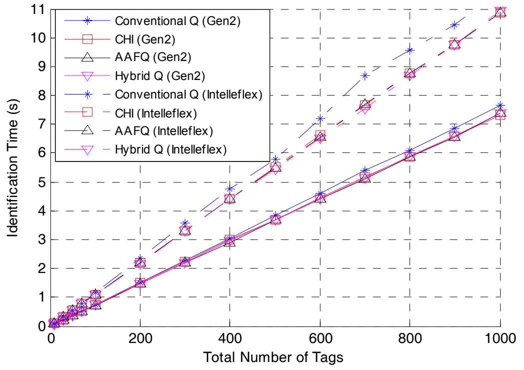

Fig. 12. Comparison between Gen2 and Intelleflex for identification time by using conventional and proposed algorithms.

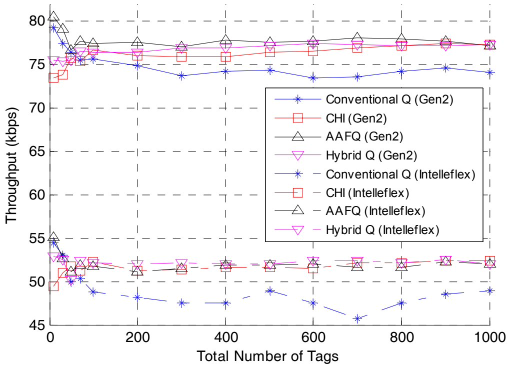

Fig. 13. Comparison between Gen2 and Intelleflex for throughput by using conventional and proposed algorithms

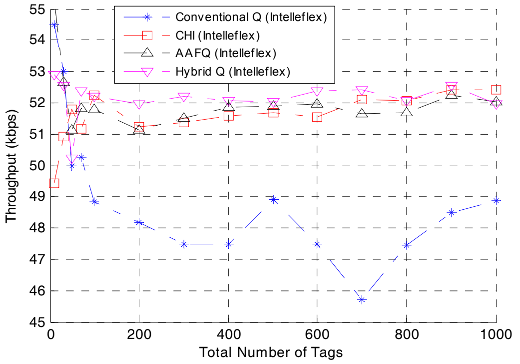

Fig. 14. Throughput of Q algorithm and the proposed algorithms in Intelleflex scenario

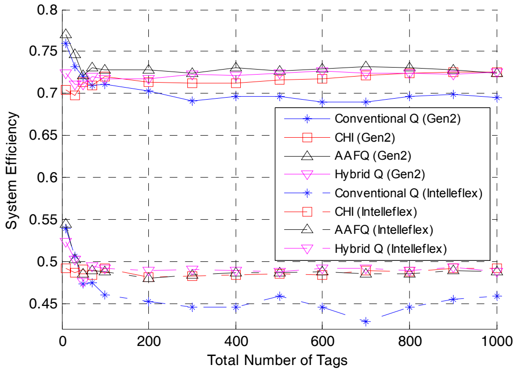

Fig. 15. Comparison between Gen2 and Intelleflex for system efficiency by using conventional and proposed algorithms

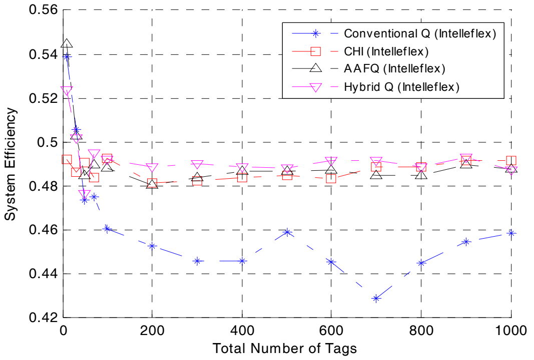

Fig. 16. System Efficiency of Q algorithm and the proposed algorithms in Intelleflex scenario

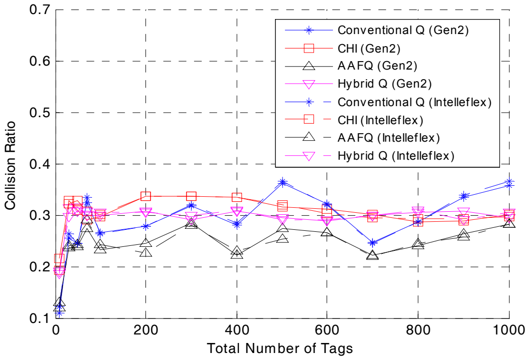

Fig. 17. Comparison between Gen2 and Intelleflex for collision ratio by using conventional and proposed algorithms

ratio in Intelleflex, which is shown in Fig. 17, is almost the same to that in Gen2. That is because collision ratio is calculated by the number of slots instead of time. Finally, we can observe that hybrid Q algorithm is the best anti-collision algorithm in Intelleflex scenario. That is, hybrid Q algorithm provides the minimum identification time, shows the more consistent collision ratio, and maximizes throughput and system efficiency in Intelleflex scenario.

V. Conclusions

In this paper, we introduce DFSA algorithm, compare the tag estimation methods for DFSA, and demonstrate Chebyshev's inequality is the best estimation method to get the optimal frame size. To increase the efficiency of tag identification, we propose new tag anti-collision algorithms which are CHI and hybrid Q algorithms, and verify the performance of identification time, throughput, system efficiency, and collision ratio for each algorithm. The performance indexes above are improved by the accurate estimation of the number of tags for tag identification. We do simulation and compare our proposed algorithms with the conventional Q algorithm and AAFQ algorithm, which is proposed in Part I[10], for both Gen2 and Intelleflex scenarios. The simulation results show that AAFQ performs the best among all the conventional and proposed algorithms in Gen2 scenario. However, in Intelleflex scenario the proposed hybrid Q algorithm is the best. That is, hybrid Q algorithm provides the minimum identification time, shows the more consistent collision ratio, and maximizes throughput and system efficiency in Intelleflex scenario.

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