Q^+-*Algorithm*: An Enhanced RFID Tag Collision Arbitration Algorithm*

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Abstract. Emerging applications of RFID require high efficiency of tag identification. Since passive tags have dumb functionality, the efficiency of tag identification in RFID system relies on the performance of the collision arbitration algorithm embedded in a reader. In this paper, we develop a novel collision arbitration algorithm, which is named Q^+-*Algorithm*, improving *Q-Algorithm* which is introduced in a standard, EPCglobal Class-1 Generation-2. We maximized the efficiency of tag identification by modifying and optimizing the parameters used in *Q-Algorithm*. Simulation-based performance evaluation proves that our scheme shows the best identification efficiency among the diverse solutions.

1 Introduction

RFID system has been expected to be the promising solution of manifold fields such as logistics, security, workflow management, and etc. An general RFID system is composed of a number of passive tags with their unique identifiers, i.e., tag ID, and a reader which recognizes tags within its range. A reader queries tag's ID with RF signal, and a tag is identified by the reader, backscattering its ID to the reader. As RFID application area is extended, it is required to deploy RFID networks in which multiple readers and passive tags can efficiently communicate with each other. Nevertheless, pondering the low cost of the passive tags, it has difficulties applying multiple access schemes such as FDMA and CDMA to passive tags. Therefore, it is needed to develop a new collision arbitration protocol through which can provide the efficient communicating between a reader and tags while keeping the simple structure of passive tags. According to whether the tag searching scheme is a depth first or a breadth first manner, RFID collision arbitration protocols are divided into two types; Aloha-based collision arbitration protocols [1]-[3] and tree-based collision arbitration protocols [4]-[6]. Based on proposed scheme in [4], binary tree using a random number generator and a

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counter which are embedded in a tag has been used in ISO/IEC 18000-6 type B [7]. In [5], Siu et al. proposed query tree that uses tag's reply that matches with the prefix of tag ID. In [6], we proposed tree-based collision arbitration algorithms through which tags can be re-identified quickly with the information of the previously identified tags. In spite of the merit of tree-based protocols such as scalability, the Aloha-based protocols are widely used in RFID standards [7]-[9] now, since the tree-based approaches have lager message overheads compared with the Aloha-based ones. Recently, EPCglobal Class-1 Generation-2 [8], the standard which uses an Aloha-based protocol, is ratified as ISO/IEC 18000-6 Type C [7]. In addition, ISO/IEC 18000-6 Type C is expected to be given a big attention as a next generation standard for UHF bandwidth. In general, there are two kinds of the Aloha-based collision arbitration which are being used in RFID systems. One is pure Aloha [1] which can be regarded as that there is no-collision arbitration in it. The other one which is now broadly used is frame-slotted Aloha (FSA) which has been advanced in function by adding slotting and framing on pure Aloha. Above all, adaptive (or dynamic) frame-slotted Aloha (adaptive FSA) algorithms have been researched [2]-[3] to optimize the performance of Aloha-based protocols. They are designed to optimize the efficiency of FSA by changing the frame sizes dynamically. In general, adaptive FSA schemes proposed up to date is comprised of two parts; tag number estimation that presumes the number of unidentified tags in reader's identification range, and frame adaptation that determines the next frame size using the estimation result at that moment. In [2], Vogt first suggested a tag estimation method for adaptive FSA in RFID system. First, it came from the assumption that the number of tags at the previous frame are at least twice of the number of collision slots. Second, it came from the assumption that the expectation of the number of each slot approximates the actual number of each one. He suggested optimal frame size adaptation on the basis of a PHILLIPS I-CODE RFID system. Cha [3] proposed a tag number estimator which uses the comparison of the actual ratio of collision slots and the expected one. Cha [3] used frame size which is the same with the number of unidentified tags by assuming that frame size is an integer. However, these schemes use integer frame sizes which are not being used in the standards. Even if it is used, it leads to a lot of overheads when a reader sends messages to tags compared with the case with frame sizes are the powers of 2.

To summarize, the schemes proposed for adaptive FSA so far mainly try to optimize utilization through the estimation of the number of unidentified tags. However, in these schemes, since the estimation algorithms make a lot of estimation errors, critical throughput degradation is supposed to happen even when the optimized frame size is used. Moreover, according to our experimental research, almost of the tag number estimation algorithms have terrible computational cost, which means that it is difficult to be applied to mobile devices with low performance. On the other side, EPCglobal Class-1 Generation-2 introduced *Q-Algorithm*, which is the prototype of a collision arbitration algorithm, without specifying parameter values used in it. *Q-Algorithm* uses a heuristical

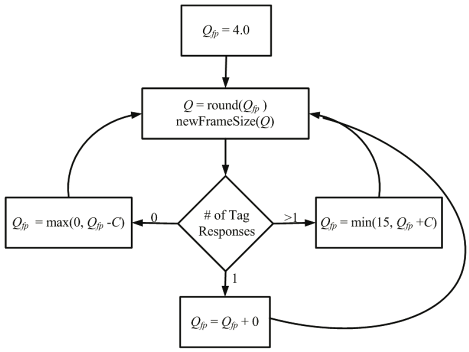


Fig. 1. The flow chart of *Q-Algorithm*: At each slot time, a reader evaluates frame size by counting the number of success, idle and collision slots

approach for converging to the optimal frame size without conducting a tag number estimation. Therefore, it wastes less computational cost than other adaptive FSA schemes.

We propose a new scheme named Q^+-*Algorithm*, which is the improvement of *Q-Algorithm*. Using this scheme, we can achieve the high recognizing efficiency with low computational cost. Although our scheme resembles the original algorithm in core structure and procedure, it is differed in optimized parameters from original one. We will show that our scheme is the optimum in terms of the efficiency of tag identification, using analytic and experimental approaches.

2 Preliminaries

In this section, we introduce *Q-Algorithm* which is introduced in EPCglobal Class-1 Generation-2 and its problems.

2.1 *Q-Algorithm*

In *Q-Algorithm*, a parameter Q denotes the exponent of frame size used in FSA. A reader using FSA sends messages to tags in order to inform the next frame size. In general, reader sends the only exponent of frame size which is denoted by 2^Q, since an integer value is not appropriate as a message format due to the overheads. Once a frame size is determined, tags choose their slot to send their ID to a reader, using a random number generator. *Q-Algorithm* is designed to evaluate tags' replies and determine the next frame size. As shown in Fig. 1, when the *Q-Algorithm* starts, it takes tags' replies slot by slot. Then, it classifies slots into three categories: success, collision and idle slot. The next frame size is updated using those three factors. Specifically, when the result of tags' replies in a slot is idle, it subtracts a constant C from Q_{fp}, because it is estimated that the used frame size is larger than ideal one. When a collision slot occurs, a constant C is added to Q_{fp}, because it means the used frame size is smaller than the number of tags. According to the standard, the range of C is from 0.1 to 0.5. Every start of each slot, it rounds Q_{fp} value. Then, new frame size Q is informed to tags. For practical uses, since messaging a size Q to tags at every slot is a redundant process, it can be omitted when Q value is not changed compared with previous one. *Q-Algorithm* has numerable advantages which are distinguished from another collision arbitration scheme using tag number estimation algorithms as follows.

– Since *Q-Algorithm* does not depend on tag number estimation method, degradation of throughput by the estimation error does not occur.
– For the same reason, even if the number of tags increases, the computation cost by tag number estimation does not increase.
– *Q-Algorithm* finds the optimal frame very quickly and does not reduce the throughput, because it evaluates the frame size in slot-by-slot manner instead of frame-by-frame one as other schemes.

In spite of these advantages, *Q-Algorithm* is not appropriate to be directly applied to RFID, since the parameters proposed in *Q-Algorithm* are not optimized. Therefore, it is required to research into this point first for the use of *Q-Algorithm*.

2.2 Optimization Problems

As stated in the previous section, *Q-Algorithm* has the advantage of the low computational cost and the property that it converges quickly to the optimal frame size. However, *Q-Algorithm* needs optimizing its parameters. The critical parameter of *Q-Algorithm* is C which determines the speed and accuracy of convergence. Before deciding the optimal value of C, we suggest several points to be considered as follows. 1) Differentiation of C: In the standard, it shows the identical C values both in collision cases and idle cases. Would this be a reasonable architecture? If it is not, we must divide the parameter C into the two different parameters and find the optimal points for each of them. 2) Scale of C: If the value of C is relatively large, the frame size converges to the optimal point very quickly. However, the oscillation will be terrible near the optimal point. On the other hand, in case of that the value of C is comparatively small, the frame size rarely changes after converging to the optimal point, but the convergence to the optimal point will be very slow. Therefore, we try to optimize *Q-Algorithm*, considering these two factors.

3 Q^+-*Algorithm*

In this section, we introduce the basic architecture of Q^+-*Algorithm*. We also introduce the optimization of the parameters used in Q^+-*Algorithm*.

Algorithm 1. Main Procedure of Q^+-*Algorithm*

```
Q_fp ← 4.0
slot number ← 0
loop
  while reader is powered
  Q ← Round(Q_fp)
  Q ← Max(Q,Q_max)
  Q ← Min(Q,Q_min)
  if Q equal to Q_old or slot number is equal to Q then
    NewFrameSize(Q)
    slot number ← 0
  else
    slot number ← slot number + 1
  end if
  Q_old ← Q
  if this slot is expired then
    slot_result ← the result of recognition in this slot.
    if slot_result == 'success' then
      Q_fp ← Q_fp + 0
    else if slot_result == 'idle' then
      Q_fp ← Q_fp − C_i
    else if slot_result == 'collision' then
      Q_fp ← Q_fp − C_c
    end if
  end if
end loop

procedure NewFrameSize(Q)
    Send a new frame size 2^Q to tags
end procedure
```

3.1 Design Rationale

Since Q^+-*Algorithm* is improved based on *Q-Algorithm*, the basic design of it is very similar to the original one. Algorithm 1 shows the main procedure of Q^+-*Algorithm*. We adopt new constants named C_i and C_c which mean the constants C for idle and collision, respectively. Specifically speaking, if a slot is diagnosed as an idle one, a reader subtracts C_i from Q_{fp}. Conversely, if a collision slot occurs, a reader adds C_c to Q_{fp}. At the end of each slot, a reader adjusts the Q value by sending a message containing a new frame size to tags. However, as we mentioned in the previous section, because the size of the message that decides a new frame size is larger than that of the message that informs the next slot, the frequent uses of new frames will bring about a lot of overheads. Therefore, in Q^+-*Algorithm*, if the value of Q is not different from that of Q_{old}, the new frame size does not be sent to tags. Optimal values of C_i and C_c will be introduced in the next section.

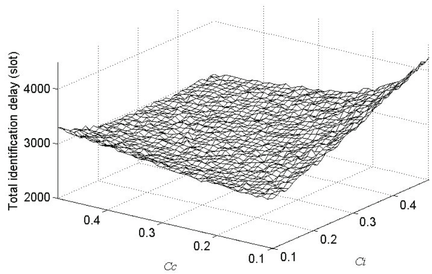


Fig. 2. Total identification delay vs. C_i and C_c when identifying 1000 tags (Test results are averaged after iterating the simulation 10 times with varying random seeds.)

3.2 Parameter Optimization

C_i and C_c are the important parameters that influence on the process of the search of the optimal frame size. Through an experiment with simulations, we analyze the effect of those parameters on the efficiency of tag identification. As shown in Fig. 2, the efficiency of tag identification, i.e., the number of consumed tags until all the tags are identified, is changed not only by the ratio of C_i to C_c but by the scale of C_i and C_c. Specifically, the plots located at relatively low delays form the shape with constant ratios, and show the different efficiencies by the scale of C_i and C_c within the identical ratios of those. Having made the above observations, we analyze and optimize C_i and C_c on these two factors: a) The ratio of C_i to C_c and b) The scale of C_i and C_c.

The ratio of C_i and C_c. To optimize the efficiency of tag identification, we conduct an analysis as follows. When the probability that a tag selects a slot in a frame is p, the distribution function which describes how many tags among m tags transmit its ID to a slot is denoted with the binomial distribution as following:

$$Pr_{m,p}(X = r) = \binom{m}{r} p^r (1-p)^{m-r} \tag{1}$$

Using Eq. (1), the successful transmission probability of a tag, which is denoted as S, can be derived as follows.

$$S = Pr_{m,p}(X = 1) = mp(1-p)^{m-1} \tag{2}$$

The condition under which S is maximized is given by,

$$\frac{dS}{dp} = m(1-p)^{m-1} - m(m-1)p(1-p)^{m-2} = 0 \tag{3}$$

Through this, the optimal condition is derived as $p = \frac{1}{m}$. Let the frame size is L, then the relationship of p and L is given by . Therefore, under the optimal condition, the relationship of L and m is written as $L = m$. Using this optimal

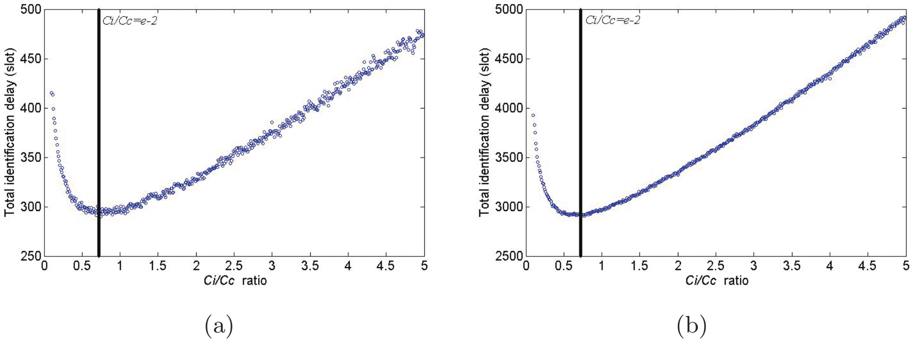


Fig. 3. Total identification delay vs. C_i/C_c ratio (Test results are averaged after iterating the simulation 100 times.) (a) Total identification delay vs. C_i/C_c ratio when identifying 100 tags, and (b) Total identification delay vs. C_i/C_c ratio when identifying 1000 tags.

condition, P^*_{idle} and P^*_{coll}, which are the probabilities denoting a slot is idle and collision under the optimal condition, respectively, are derived as follows.

$$P^*_{idle|m,L} = Pr_{m,p}(X = 0|L = m) = \left(1 - \frac{1}{m}\right)^m \tag{4}$$

$$P^*_{coll|m,L} = Pr_{m,p}(X \geq 2|L = m) = \left(1 - \frac{1}{m}\right)^m \left(1 + \frac{m}{m-1}\right) \tag{5}$$

As m is taken to infinity, P^*_{idle} and P^*_{coll}, which are asymptotical proportions of idle and collision slots under the optimal condition, respectively, are given by,

$$P^*_{idle} = \lim_{m\to\infty} Pr_{m,p}(X = 0|L = m) = \frac{1}{e} \tag{6}$$

$$P^*_{coll} = \lim_{m\to\infty} Pr_{m,p}(X \geq 2|L = m) = \left(1 - \frac{2}{e}\right) \simeq 0.264 \tag{7}$$

If the Q value is the optimal, Q must not to be changed at all at that point. For this reason, by an intuitive view, it is clarified that the ratio of C_i to C_c under the optimal condition has a reciprocal relationship with the proportion of collision slots to idle slots in the same condition. Accordingly, we get the optimal ratio of C_i to C_c as the following equation.

$$\frac{C_i}{C_c} = \frac{P^*_{coll}}{P^*_{idle}} = e - 2(\simeq 0.71828) \tag{8}$$

Finally, this allows us to know that the optimal ratio of C_i to C_c is $e - 2$. The optimal ratio is verified in Fig. 3. The optimal ratio is located near $e - 2$ both in Fig. 3(a) and Fig. 3(b).

Scale of C_i and C_c. Although the optimal ratio of C_i to C_c is derived, according to Fig. 2, it shows the slight differences of efficiency by the scale of C_i and C_c within the analogous ratio of those. According to our experimental researches, the optimal ratio of C_i and C_c has a dependency on the number of unidentified tags, though there is no relationship between the optimal ratio and the number of tags. A simulation is conducted to find the optimal scale of C_i and C_c with respect to the number of unidentified tags. As the number of tags increases, Table 1 shows that the point with the optimal scale decreases while the number of tags is below 1500, but it converges to around 0.17 as the number of tags increases over 1500. Based on these observation results, we make the logarithmic approximation for the optimal scale of C_c with the least-square method. Note that this function is for the case of that the number of tags is predetermined.

$$\textit{optimal } C_c = -0.0491 \ln(m) + 0.534 \tag{9}$$

Final solution. Having performed preceding analysis, the final solution is given as follows.

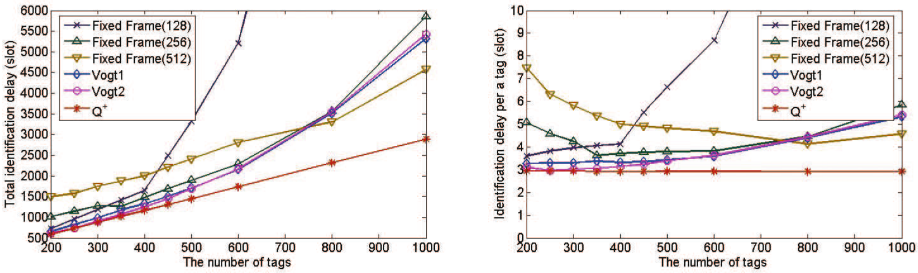
If the number of tags is known,
$C_c = -0.0491 \ln(m) + 0.534$
$C_i = (e - 2) \cdot C_c$

If the number of tags is unknown,
$C_c =$ set arbitrarily between 0.1 and 0.5
$C_i = (e - 2) \cdot C_c$

As shown above, the value of C_c is not specified when the number of tags is unknown. However, according to our experimental study, even though C_c is randomly selected, it shows slight influence on the throughput. Our experiment results confirmed this with showing the fact that the difference between the maximum slot delay and the minimum slot delay is at maximum 80 slots. As a result, it is revealed that the ratio of C_i to C_c is more critical factor than the scale of those.

Table 1. Optimal C_c when C_i/C_c ratio is fixed to $e - 2$

The number of tags	**The optimal C_c**
100	0.35
300	0.22
500	0.21
1000	0.17
1500	0.16
2000	0.17
3000	0.18



(a) (b)

Fig. 4. Simulation Results: (a) Total identification delay vs. the number of tags, and (b) Marginal identification cost vs. the number of tags

4 Performance Evaluation

In this section, we compare Q^+-*Algorithm* with other algorithms by evaluating them through the simulation which is developed with Microsoft Visual C++ 6.0. Q^+-*Algorithm* uses the final solution that is proposed in section 3.2. For the fairness with other algorithms, we assume that the initially given number of tags is unknown. For this reason, the value of C_c of Q^+-*Algorithm* is fixed as 0.35. Q^+-*Algorithm* is compared with the two adaptive FSA algorithms proposed by Vogt [2], the fixed frame size with 128(=27), 256(=28), and 512(=29). The algorithm proposed in [3] is not considered for the comparison, because they do not use the frame size with powers of 2. For the sake of convenience, we name the algorithm that uses the tag number estimator with the double of collision slots Vogt1 and the algorithm that uses the property of Chebyshv's inequality Vogt2. For the evaluation in terms of the identification efficiency, we counted the all slots consumed for identifying all given tags. In each simulation, the number of given tags is changed from 200 to 1000. All the results of the simulation are averaged after iterating it 100 times.

4.1 Total Identification Delay

The total identification delay means the number of the all consumed slots until all tags are recognized by a reader. The fewer slots consumed in an algorithm, the better algorithm it is. Fig. 4(a) describes that Q^+-*Algorithm* outperforms other algorithms in terms of total identification delay. Vogt1 and 2 show the higher total identification delay as the number of tags increases. This mainly comes from the fact that the tag number estimator does not work well with many tags. The cases with fixed frame also show low throughput as the number of tags increases, except the case of the frame size with 512. In case of frame size with 512, it shows terrible efficiency below 800 slots. These results prove that the performance of an adaptive FSA algorithm depends on its adaptability.

4.2 Marginal Identification Cost

The marginal identification cost denotes the average slots used for identifying a tag. This is a good indicator for the scalability of an adaptive FSA algorithm. To know this, we divided results on the total delay by the number of tags. As shown in Fig. 4(b). Q^+-*Algorithm* constantly shows the outstanding performance regardless the number of tags. A brilliant fact we found is that the marginal identification cost of Q^+-*Algorithm* very closely approaches e, i.e., the theoretically optimal marginal identification cost in adaptive FSA algorithms.

5 Conclusions and Future Works

In this paper, we proposed Q^+-*Algorithm*, which is an enhanced adaptive FSA algorithm for RFID tag collision arbitration. We introduced new parameters C_i and C_c in addition to the basic architecture of *Q-Algorithm*. Our performance evaluation demonstrated that proposed scheme shows predominant performance compared with other solutions. In addition, Q^+-*Algorithm* does not have drawbacks like the overheads and the errors which are generated by a tag number estimation, and it does not require the modification of tag architecture or standards. Therefore, it is expected that our scheme can be applied widely for improving the efficiency of RFID systems.

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