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An Adaptive Memoryless Protocol for RFID Tag Collision Arbitration

Jihoon Myung, Wonjun Lee, and Timothy K. Shih

***Abstract*—A radio frequency identification (RFID) reader recognizes objects through wireless communications with RFID tags. Tag collision arbitration for passive tags is a significant issue for fast tag identification due to communication over a shared wireless channel. This paper presents an *adaptive memoryless protocol*, which is an improvement on the query tree protocol. *Memoryless* means that tags need not have additional memory except ID for identification. To reduce collisions and identify tags promptly, we use information obtained from the last process of tag identification at a reader. Our performance evaluation shows that the adaptive memoryless protocol causes fewer collisions and takes shorter delay for recognizing all tags while preserving lower communication overhead than other tree based tag anticollision protocols.**

***Index Terms*—Collision resolution, RFID, tag anticollision, tag identification.**

I. Introduction

Radio frequency identification (RFID) system is an automatic identification mechanism. A reader recognizes objects through wireless communications with tags, which are attached to objects and have a unique ID [1]. The reader must be able to identify tags as quickly as possible. However, signals transmitted simultaneously by readers or tags collide because they communicate over a shared wireless channel. Collisions interfere with fast tag identification and the reader may not recognize all tags due to the collisions. Therefore, anticollision protocols, which reduce collisions and identify tags regardless of the occurrence of collisions, are required.

Collisions are divided into reader collisions and tag collisions [2]. Reader collisions occur when neighboring readers interrogate a tag simultaneously. Tag collisions occur when multiple tags try to transmit ID to the same reader at the same time and prevent the reader from recognizing any tag. Reader collisions can be resolved because RFID readers can detect collisions and communicate with one another. On the other hand, low-functional passive tags, which transmit their IDs to the reader by reflecting the waves emitted from the reader, can neither figure out neighboring tags nor detect collisions. Therefore, CSMA-related methods are not practically applicable to tag collision arbitration for passive tags [3] and tag anticollision protocols for passive tags are important.

Tag anticollision protocols can be grouped into two broad categories, aloha based protocols and tree based protocols. Aloha based protocols [4]–[9] reduce the occurrence probability of tag collisions since tags transmit at distinct time slots. Aloha based protocols, however, cannot completely prevent collisions. In addition, the mechanisms have a serious problem that a specific tag may not be identified for a long time, leading to the so called *tag starvation problem*. The tree based protocols use the splitting mechanism for tag identification. When tag collision occurs, they split a set of colliding tags into two subsets. The reader then attempts to recognize the subsets one by one. By splitting until the reader receives tag signals without collisions, the reader can recognize all the tags inside its own identification range. For splitting the tag set, the binary tree protocol [9]–[12] uses random binary numbers, and the query tree protocol [13], [14] uses tag IDs. Although tree based protocols do not cause tag starvation problem, they have relatively long identification delay caused by the splitting procedure starting from one set which includes all tags [3].

Based on the above analysis, a good tag anticollision protocol for passive RFID tags should have the following characteristics. First, a reader ought to recognize all the tags inside its own identification range. Tag identification missing a tag results in the failure of object tracking and monitoring. Since the reader cannot presume the number of tags precisely, a guarantee of recognizing all tags must be taken into consideration in the design of a tag anticollision protocol. Second, a reader has to recognize tags promptly. Since an object with a tag is potentially mobile, tag identification must keep face with the object's velocity. The reader cannot recognize the object if tag identification is carried out slower than the object's velocity. Finally, a tag should be recognized while consuming a small amount of resource. Since a passive tag supplements power from the reader's wave, tag's available power is limited. A tag also has low computational capability and limited memory. Thus, tag anticollision protocol must load a tag with the least possible communication and computation overheads.

We propose an *adaptive memoryless protocol* for fast tag identification with less collision. *Memoryless* means that tags need not have additional memory except ID for identification. For decreasing collisions, the proposed protocol exploits information obtained from the last identification process at a reader in an environment where a reader executes tag identification repeatedly for object monitoring and tracking. The reduction in collisions facilitates tag identification with a small delay and few transmissions while recognizing all tags. The simulation results show that the adaptive memoryless protocol suppresses the occurrence of collisions and shortens total delay for recognizing all tags while preserving low communication overhead. The rest of this paper is organized as follows. Section II shows problems of the existing tree based protocols. Section III describes our adaptive memoryless protocol. In Section IV and Section V, the performance analysis, including the derivations of several major equations referred to in the analysis, is presented. Finally the conclusions of our analysis are presented in Section VI.

II. Problem Description

Tag identification in tree based tag anticollision protocols is coincident with a tree search which finds nodes of either one tag transmission or no tag transmission. Each node in the tree is associated with a reading cycle where the reader transmits a query or feedback and then tags respond. The binary tree protocol and the query tree protocol begin tag identification at the root of the tree as shown in Fig. 1.

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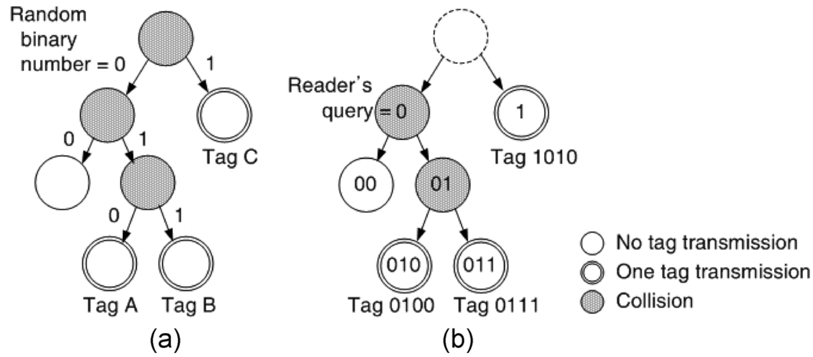


Fig. 1. Tag identification in tree based protocols; (a) binary tree protocol and (b) query tree protocol.

We assume that a reader performs tag identification processes repeatedly for object tracking and monitoring. For reader r, let A_i be the set of tags which dwell inside the identification range of reader r during the ith identification process of reader r. To consider the tag's mobility, we classify tags into *staying tags*, *arriving tags*, and *leaving tags*. Tag a_s is the staying tag in the ith process of reader r if $a_s \in A_{i-1} \cap A_i$. Tag a_a is the arriving tag in the ith process of reader r if $a_a \in A_i - A_{i-1}$. Tag a_l is the leaving tag in the ith process of reader r if $a_l \in A_{i-1} - A_i$. Tag identification should recognize staying tags and arriving tags promptly.

Staying tags have been recognized in the last identification process and the reader will re-recognizes staying tags in the current identification process. Since the reader already knows information on staying tags, tag collision arbitration can prevent collisions between signals transmitted by staying tags during the current process. However, the existing tree based tag anticollision protocols cause collisions between staying tags and make long delay because they do not take staying tags into consideration. At the beginning of the identification process, the binary tree protocol and the query tree protocol make one set, which includes all the tags inside the reader's identification range, and start the splitting procedure.

When tag collision occurs in tag identification of tree-based protocols, colliding tags need re-transmit their IDs. Resolution of tag collisions consumes the tag's limited energy and additional time. Therefore, eliminating collisions among staying tags can shorten the total delay for tag identification and reduce the tag's communication overhead. The adaptive memoryless protocol adaptively and efficiently decides the starting points of the tree search by using information on the tags recognized in the last identification process and skips nodes which caused collisions in the last process. Hence, the adaptive memoryless protocol prevents collisions between staying tags by the splitting procedure starting from several tag sets; each of sets has one staying tag at most. It is still simple and recognizes all tags quickly.

III. Adaptive Memoryless Protocol

In the adaptive memoryless protocol, the tag transmission is controlled by reader's queries analogous to the query tree protocol. Tags are *memoryless* because they do not maintain any information except their own IDs. To eliminate collisions between staying tags, the reader does not transmit queries that multiple tags responded in the last identification process. The key institution behind our proposed approach is that in most applications employing passive RFID tags, the set of objects encountered in successive readings from a particular reader does not change substantially and information from one reading can be used for the next.

A. Basic Operation

The reader transmits a query and tags respond with their IDs. The query includes a bit string. The tag is allowed to respond if $r_1 r_2 \ldots r_x = q_1 q_2 \ldots q_x$ where the tag ID is $r_1 r_2 \ldots r_b$ (r_i is a binary value, b is the number of bits of ID) and the query is $q_1 q_2 \ldots q_x$ (q_i is a binary value, $1 \leq x \leq b$).

The reader has queue Q and candidate queue CQ. Q maintains queries for the current identification process. CQ compiles queries for the next identification process. At the beginning of the process, the reader initializes Q with queries of CQ. When CQ does not have any query (e.g., when the reader resets), Q is initialized with two 1-bit queries, 0 and 1, as the query tree protocol. The reader dequeues (i.e., removes from queue and returns) a query from Q and transmits it. The tag identification process continues until Q is empty.

B. Query Insertion

Let $q_1 q_2 \ldots q_x$ be the transmitted query. According to the number of tag responses, queries are categorized as follows.

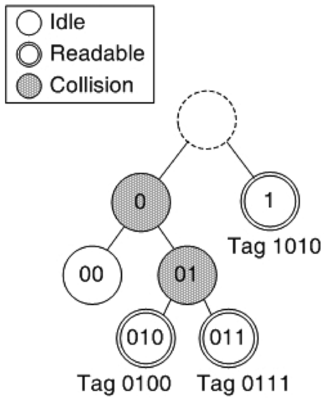
- *Idle*: No tag responds. The idle query does not make the reader fail to recognize a tag, but it is a source of unnecessary increment of identification delay. The reader en-queues (i.e., adds to queue) $q_1 q_2 \ldots q_x$ into CQ.
- *Readable*: Only one tag responds to the query, and it is recognized by the reader successfully. To recognize all tags, the number of readable queries transmitted in an identification process should be equal to the number of tags. The reader en-queues $q_1 q_2 \ldots q_x$ into CQ.
- *Collision*: Multiple tags respond and the tag-to-reader signals collide. The reader is unable to recognize any tag. The collision query defers tag identification and the tag's communication is pure overhead. The reader en-queues $q_1 q_2 \ldots q_x 0$ and $q_1 q_2 \ldots q_x 1$ into Q.

To split colliding tags into two subsets, the reader en-queues two queries 1-bit longer than the collision query into Q. Expanding the collision queries enables the reader to recognize all tags. CQ stores idle queries as well as readable queries. Eliminating collisions between staying tags in the next process is achieved by readable queries. Since the reader does not know an arriving tag's ID in advance, idle queries are used for recognizing arriving tags in the next process.

Fig. 2 shows an tag identification process when the reader resets (CQ has no query and tag identification of the adaptive memoryless protocol is the same as one of the query tree protocol) and there are three tags whose IDs are 0100, 0111, and 1010, respectively. A bit string in a node indicates a reader's query. Recognizing three tags causes two collisions and CQ stores 1, 00, 010, and 011. Consider the situation that the reader reattempts to recognize the same tags again. In order words, all the tags are staying tags and there is no arriving tag and no leaving tag. As shown in Fig. 3, there are no collisions.

C. Query Deletion

In performing the query insertion procedure, the starting points of the tag identification go downward toward the child nodes of the tree. The



Step	Reader query	Tag responses			Q	CQ
		Tag 0100	Tag 0111	Tag 1010		
0					0, 1	
1	0	**0**100	**0**111		1, 00, 01	
2	1			**1**010	00, 01	1
3	00				01	1, 00
4	01	**01**00	**01**11		010, 011	1, 00
5	010	**010**0			011	1, 00, 010
6	011		**011**1			1, 00, 010, 011

Fig. 2. Tag identification of the adaptive memoryless protocol after the reader resets.

query deletion procedure make the starting points go upward toward the root of the tree.

Since more than one response follows the collision query, only a tree node of a collision query has two child nodes which are a pair of node types as follows: 1) two collision queries, 2) a collision query and a readable query, 3) a collision query and an idle query, and 4) two readable queries. Leaving tags make abnormal queries as follows.

- *A readable query and an idle query*: Only a tag responds to $q_1q_2\ldots q_x$ without collision if one of $q_1q_2\ldots q_x0$ and $q_1q_2\ldots q_x1$ corresponds to the readable query and the other corresponds to the idle query. $q_1q_2\ldots q_x$ is the reader query.
- *Two idle queries*: No tag responds to $q_1q_2\ldots q_x$ if $q_1q_2\ldots q_x0$ and $q_1q_2\ldots q_x1$ correspond to idle queries. Therefore, $q_1q_2\ldots q_x$ is also idle.

When $q_1q_2\ldots q_x0$ and $q_1q_2\ldots q_x1$ is abnormal queries, the reader deletes $q_1q_2\ldots q_x0$ and $q_1q_2\ldots q_x1$ from CQ and en-queues $q_1q_2\ldots q_x$ into CQ. After a process, the reader deletes all transformed queries from CQ recursively. As the query deletion is done under the condition that all branches in the tree are included in CQ, all tags are recognized promptly.

Fig. 4 shows the operation of the query deletion procedure when tag 0111 becomes the leaving tag after tag identification illustrated in Fig. 3. Query 011 changes into the idle query from the readable query. By the query deletion procedure, the reader successfully recognizes tag 0100 and tag 1010 with two queries, 0 and 1, respectively.

IV. Performance Analysis

In this section, we analyze properties and discuss the worst-case delay of the adaptive memoryless protocol.

Lemma 1: All tags are recognized by queries of all leaf nodes in the tree.

Proof: A 1-bit query, 0 (or 1) recognizes all tags of which the first bit of IDs is 0 (or 1) if it is a query of a leaf node in the tree. For any $q_1q_2\ldots q_x$, all tags which match $q_1q_2\ldots q_x$ are recognized by $q_1q_2\ldots q_x0$ and $q_1q_2\ldots q_x1$. Therefore, any tag can be recognized by all leaf nodes in the tree. □

Theorem 1: The adaptive memoryless protocol recognizes all the tags in the reader's identification range.

Proof: The reader transmits $q_1q_2\ldots q_x0$ and $q_1q_2\ldots q_x1$ if $q_1q_2\ldots q_x$ causes collision. Hence, all the intermediate nodes in the tree correspond to collision queries and all the leaf nodes correspond to either readable queries or idle queries. By lemma 1, the adaptive memoryless protocol recognizes all the tags by readable queries and idle queries. □

Theorem 2: Maintaining CQ does not need additional memory of the reader.

Proof: Let $S_Q(x)$ and $S_{CQ}(x)$ be the number of bits of queries in Q and in CQ, respectively, after transmitting the xth query. When a new process starts, $S_{CQ}(0)=0$. Let $l(x)$ denote as the number of bits of the xth query. For $x>0$,

$$S_Q(x) = S_Q(x-1) - l(x) + 2c(x)\,(l(x)+1) \tag{1}$$

$$S_{CQ}(x) = S_{CQ}(x-1) + (1-c(x))\,l(x) \tag{2}$$

where $c(x)=1$ if the xth query is the collision query; $c(x)=0$ otherwise. $S_{CQ}(x)$ increases if the xth query is not the collision query. However, the total size of Q and CQ is not changed. Therefore, maintaining CQ does not require additional memory. □

Definition 1: Let A_i be the set of tags recognized in the ith process. The identification delay for recognizing A_i, $d_{total}(A_i)$, is

$$d_{total}(A_i) = \sum_{q\in S(A_i)} (d_{reader}(q) + d_{tag}) \approx T(A_i)\cdot d_{cycle} \tag{3}$$

where $S(A_i)$ is the set of queries required for recognizing A_i, $d_{reader}(q)$ is the delay of delivering query q, d_{tag} is the delay of delivering the tag ID, d_{cycle} is the average time period of a reading cycle, and $T(A_i)$ is the number of queries required for recognizing A_i. The total delay is determined by $T(A_i)$.

For the analysis of the identification delay, we consider a single reader that recognizes n tags, each of which has a unique b-bit ID. A_i has n tags. Let α and β be the number of arriving tags and leaving tags, respectively, in the ith process.

Lemma 2: Let $C_{QT}(A_i)$ denote as the number of collision queries caused by the query tree protocol recognizing A_i. Given $C_{QT}(A_i)$, the identification delay of the query tree protocol recognizing A_i, $T_{QT}(A_i)$, is

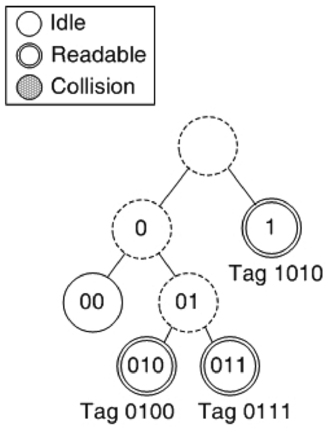
$$T_{QT}(A_i) = 2C_{QT}(A_i) + 1 \tag{4}$$

Proof: By the proof of theorem 1, only a node with a collision query has two child nodes. The tree is a full binary tree, and all the intermediate nodes correspond to collision queries. □

Lemma 3: For any set of n tags:

$$T_{QT}(A_i) \le n(b + 2 - \log_2 n) - 3. \tag{5}$$

Proof: By lemma 2, the worst case of the identification delay in the query tree protocol is that collisions are most numerous. Since each tag has a unique b-bit ID, two tags' IDs can, at most, be equal to the first $b-1$ bits except the last bit. Thus, two tags make $b-1$ collisions. In the tree, a node can be a collision query when multiple tags select



Step	Reader query	Tag responses			Q	CQ
		Tag 0100	Tag 0111	Tag 1010		
0					1, 00, 010, 011	
1	1			**1**010	00, 010, 011	1
2	00				010, 011	1, 00
3	010	**010**0			011	1, 00, 010
4	011		**011**1			1, 00, 010, 011

Fig. 3. Tag identification by the query insertion procedure.

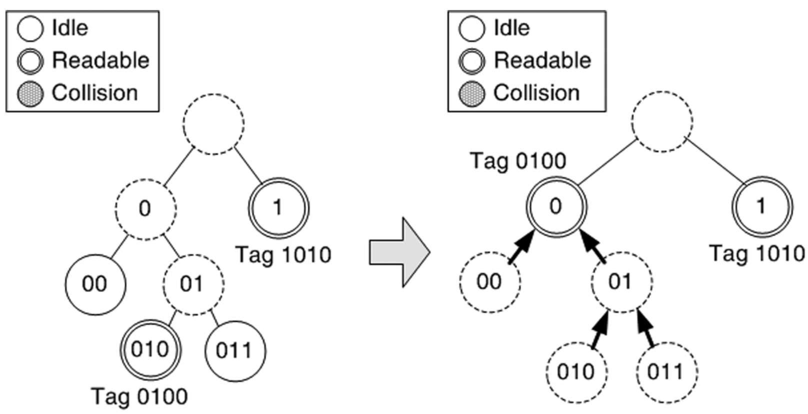


Fig. 4. Query deletion procedure after tag 0111 reaches out of the reader's identification range.

it for transmission. The maximum number of collision queries in the depth k of the tree for recognizing n tags, $C_{QT}(n,k)$, is

$$C_{QT}(n,k) = \begin{cases} 2^k & \text{if } 0 \le k \le \log_2 n - 1 \\ n/2 & \text{if } \log_2 n - 1 < k < b \end{cases} \tag{6}$$

$$C_{QT}(A_i) \le \sum_{k=0}^{b-1} C_{QT}(n,k) \le \frac{n}{2}(b + 2 - \log_2 n) - 2 \tag{7}$$

$$T_{QT}(A_i) = 2C_{QT}(A_i) + 1 \le n(b + 2 - \log_2 n) - 3. \tag{8}$$

□

Lemma 4: Let $T_{AM}(A_i|A_{i-1})$ denote the number of queries transmitted by the adaptive memoryless protocol recognizing A_i after having recognized A_{i-1}. When $\alpha = 0$ and $\beta = 0$,

$$T_{AM}(A_i|A_{i-1}) \le \frac{n}{2}(b + 2 - \log_2 n) - 1. \tag{9}$$

Proof: The adaptive memoryless protocol initializes Q with the queries of the leaf nodes in the tree produced during the $i-1$th process. Hence, the queries transmitted in the ith process are either the readable queries or the idle queries. Let $L_{QT}(A_i)$ denote as the number of leaf nodes in the tree produced by the query tree protocol recognizing A_i. Then,

$$T_{AM}(A_i|A_{i-1}) = L_{QT}(A_i) = C_{QT}(A_i) + 1 \tag{10}$$

Lemma 4 is derived by (7). □

Lemma 5: When $\alpha > 0$ and $\beta = 0$,

$$T_{AM}(A_i|A_{i-1}) \le n(b + 2 - \log_2 n) - (n - \alpha + 2) \tag{11}$$

Proof: The adaptive memoryless protocol initializes Q with the queries of the leaf nodes in the tree of the ith process. Since $A_{i-1} \subset A_i$, the tree of the $i-1$th process is the part of the tree of the ith process.

$$\begin{aligned} T_{AM}(A_i|A_{i-1}) &= T_{QT}(A_i) - T_{QT}(A_{i-1}) + L_{QT}(A_{i-1}) \\ &= T_{QT}(A_i) - C_{QT}(A_{i-1}) \end{aligned} \tag{12}$$

The minimum of $C_{QT}(A_{i-1})$ is $n-\alpha-1$ when $L_{QT}(A_{i-1})$ is $n-\alpha$, that is, all the leaf nodes correspond to the readable queries. The adaptive memoryless protocol reduces at least $n-\alpha-1$ queries compared with the query tree protocol. □

Lemma 6: When $\alpha = 0$ and $\beta > 0$,

$$T_{AM}(A_i|A_{i-1}) \le \frac{n}{2}(b + 2 - \log_2 n) - 1. \tag{13}$$

Proof: The adaptive memoryless protocol can eliminate idle queries caused by leaving tags after the reader has detected nonexistence tags. Since the reader does not know leaving tags in the ith process, the identification delay of the ith process is the same as one of the $i-1$th process. □

Theorem 3: When $\alpha > 0$ and $\beta > 0$,

$$T_{AM}(A_i|A_{i-1}) \le n(b + 2 - \log_2 n) - (n - \alpha + 2) \tag{14}$$

Proof: This is derived straight from lemma 5 and 6. □

V. Performance Evaluation

We evaluate the performance of the adaptive memoryless protocol compared to the binary tree protocol and the query tree protocol. The

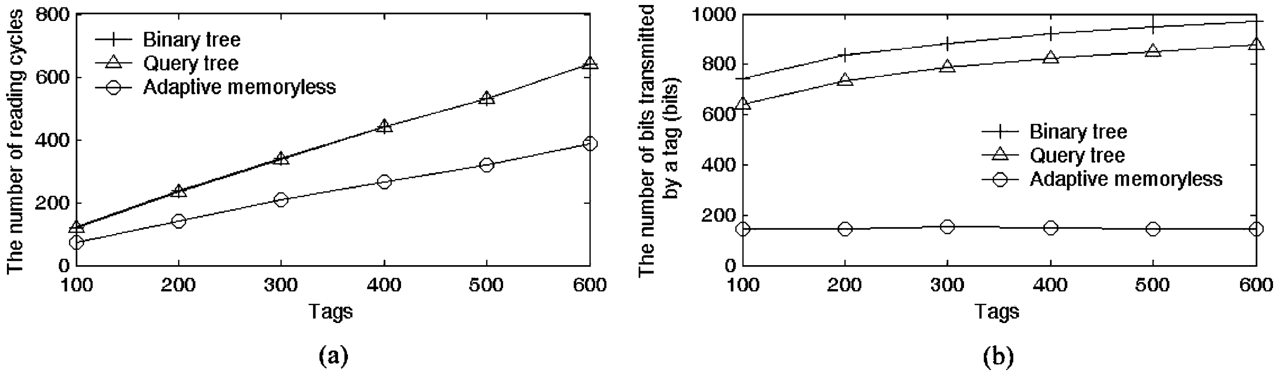


Fig. 5. Performance comparison with varying the number of tags: (a) identification delay and (b) tag communication overhead.

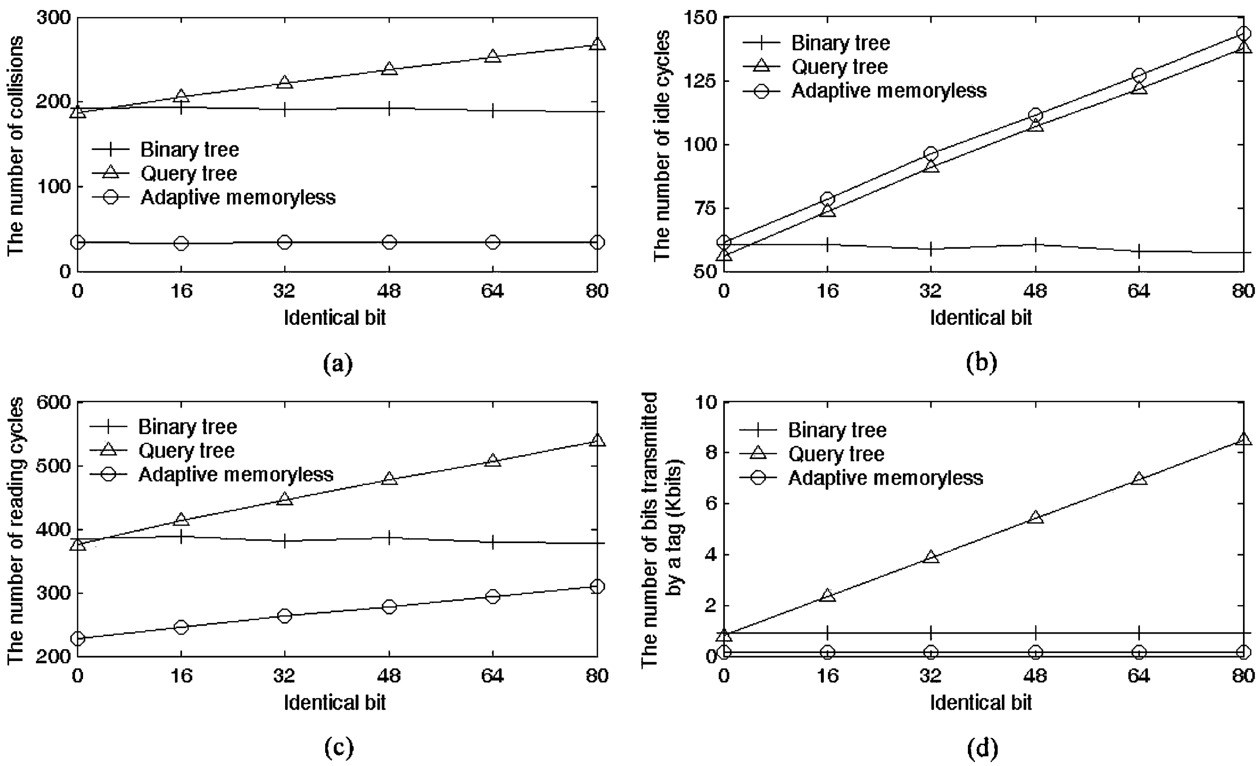


Fig. 6. Performance comparison with varying the number of tags: (a) collisions, (b) idle cycles, (c) identification delay, and (d) tag communication overhead.

simulation area is 10 m $\times$ 10 m. The reader is located in the center of the simulation area and its reading range is 3 m. Tag mobility follows the *random walk model* [15] with the maximum speed of 2 m/process. Total delay for recognizing all the tags is assessed by the number of reading cycles. Tag communications overhead is measured by the average number of bits transmitted by each of the tags in order to be recognized.

A. Impact of the Number of Tags

Fig. 5 and Table I give the results obtained by changing the number of tags. Each tag has a randomly selected 96-bit ID. We simulate tag anticollision protocols with 100, 200, 300, 400, 500, and 600 tags and the average number of tags in the reader's reading range is 42.5, 81.93, 118.18, 152.63, 184, and 223.27, respectively. An "idle cycle" means the reading cycle when no tag responds. As the number of tags increases, the identification delay gets longer and tag signals collide more often. The binary tree protocol and the query tree protocol show almost similar results of the identification delay and the number of collisions. The binary tree protocol imposes a heavy communication overhead on a tag because the tag transmission is decided by the tag's random number generator without the assistance of the reader. It is a shortcoming that the low-cost and low-functional tags transmit more signals. The adaptive memoryless protocol, however, degenerates very slowly and has the shortest delay for recognizing all the tags. The tags also transmit very small bits because most of collision queries and unnecessary idle queries are not transmitted.

B. Impact of the Similarity of Tag ID

For the purpose of additional comparison, we evaluated the impact of the similarity among IDs. The query tree protocol and the adaptive memoryless protocol may be influenced by the distribution of IDs because they use IDs for splitting. To quantify the similarity of IDs, we define an identical bit, γ. ID is depicted by $x_1 x_2 \ldots x_\gamma x_{\gamma+1} \ldots x_{96}$ (x_i is a binary digit, $1 \leq \gamma < 96$) and all tags have the same $x_1 x_2 \ldots x_\gamma$ when each tag has a 96-bit ID. Fig. 6 gives the simulation results for various identical bits from 0 (IDs are completely randomly selected)

TABLE I
IDENTIFICATION DELAY ACCORDING TO THE NUMBER OF TAGS

Tags	Protocol	Collisions	Idle cycles	Delay
100	Binary tree	60.18	18.68	121.36
	Query tree	58.83	18.33	119.66
	Adaptive memoryless	10.66	20.44	73.6
200	Binary tree	117.86	36.93	236.72
	Query tree	115.57	35.64	233.14
	Adaptive memoryless	19.88	38.74	140.55
300	Binary tree	169.22	52.04	339.44
	Query tree	168.46	52.28	338.92
	Adaptive memoryless	32.77	56.95	207.9
400	Binary tree	220.48	68.85	441.96
	Query tree	218.79	68.16	439.58
	Adaptive memoryless	39.18	74.85	266.66
500	Binary tree	264.55	81.55	530.1
	Query tree	263.79	81.79	529.58
	Adaptive memoryless	46.37	88.9	319.27
600	Binary tree	320.8	98.53	642.6
	Query tree	320.36	99.09	642.72
	Adaptive memoryless	56.21	108.45	387.93

to 80. To assess impact of ID distribution precisely, we normalize the measured values by dividing the number of recognized tags. As the similarity of IDs increases, the query tree protocol rapidly degenerates as expected. The query tree protocol has the highest communication overhead because the reader transmits all collision queries in every frame. On the other hand, the performance of the adaptive memoryless protocol is rarely affected by the similarity of IDs. Since the query insertion procedure excludes collision queries, the adaptive memoryless protocol uses a collision query only once. However, the number of idle cycles increases due to the increment of the leaf nodes necessary to guarantee recognizing all tags. The adaptive memoryless protocol eminently outperforms than other tree based protocols though it is affected by the similarity of IDs.

VI. CONCLUSION

In this paper, an adaptive memoryless tag anticollision protocol for passive RFID tags has been proposed and evaluated. Collision caused by tags transmitting simultaneously is a major factor in deferring tag identification of the RFID system. Our contributions include development of a novel and enhanced query tree protocol to reduce the identification delay by using queries which do not cause collisions. The key institution behind our proposed approach is that in most applications employing RFID tags, the set of objects encountered in successive readings from a particular reader does not change substantially, and information from one reading can be used for the next. A simulation-based evaluation shows that the adaptive memoryless protocol significantly reduces delay and communication overhead for the tag reading process.

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