FTTP: A Fast Tree Traversal Protocol for Efficient Tag Identification in RFID Networks

Jihoon Choi, *Student Member, IEEE,* Inkyu Lee, *Senior Member, IEEE,* Ding-Zhu Du, *Member, IEEE,* and Wonjun Lee, *Senior Member, IEEE*

***Abstract*—This letter presents an efficient tag collision arbitration protocol, viz., the Fast Tree Traversal Protocol (FTTP). It estimates the number of tags using maximum likelihood estimation and adjusts the splitting factor to reduce the identification delay. We show that our protocol effectively reduces the identification delay via the performance analysis and simulation results.**

***Index Terms*—RFID, collision arbitration, RFID tag anti-collision.**

I. Introduction

RADIO Frequency Identification (RFID) is an emerging technology capable of automatically detecting objects. The identification procedure known as tag collision arbitration has a significant impact on the performance of RFID networks. Speaking broadly, two types of tag collision arbitration protocols have been proposed: aloha-based and tree-based. We focus on the tree-based protocols, because a smart trend traversal protocol (STT) which outperforms aloha protocols is proposed [1] and there is still room to improve. Tree-based protocols are divided into two groups (BT and QT) according to which identifiers are used for splitting tags: random numbers or ID prefixes. The Binary-tree protocol (BT) was initially used in the ISO/IEC 18000-6 standard [2], and the Query-tree protocol (QT) is proposed in [3].

Since BT and QT always split tags into two groups, they can cause considerable collisions. To reduce collisions, STT, a QT-based protocol, finds a proper tree traversal path (TTP) using sequential arrangements of tags. However, since QT-based protocols use ID prefixes to split tags, they have two disadvantages. First, the long length of the ID prefix can cause a large delay in each slot. Second, the identification delay depends on the distribution tag IDs.

Many existing arbitration protocols including BT, QT, and STT have no consideration for different slot durations. In fact, slot durations generally differ by their type (success, collision and idle). For instance, in ISO 18000-6 type B, the duration of a collision slot is longer than that of an idle slot. This example bolsters our notion that the main objective of an arbitration protocol should be to minimize the identification delay, not the number of slots.

Manuscript received April 4, 2010. The associate editor coordinating the review of this letter and approving it for publication was C.-F. Chiasserini.

This research was jointly supported by MEST, Korea, under WCU (R33-2008-000-10044-0), a KOSEF Grant funded by the Korean Government (MEST) (No. R01-2007-000-11203-0), a KRF Grant (KRF-2008-314-D00354), and MKE, Korea under ITRC NIPA-2010-(C1090-1021-0008).

W. Lee (corresponding author) and J. Choi are with the Dept. of Computer Science and Engineering, Korea University, Seoul, Korea (e-mail: wlee@korea.ac.kr).

I. Lee is with the School of Electrical Engineering, Korea University, Seoul, Korea.

D.-Z. Du is with the Dept. of Computer Science, University of Texas at Dallas, Richardson, TX, USA.

Digital Object Identifier 10.1109/LCOMM.2010.08.100539

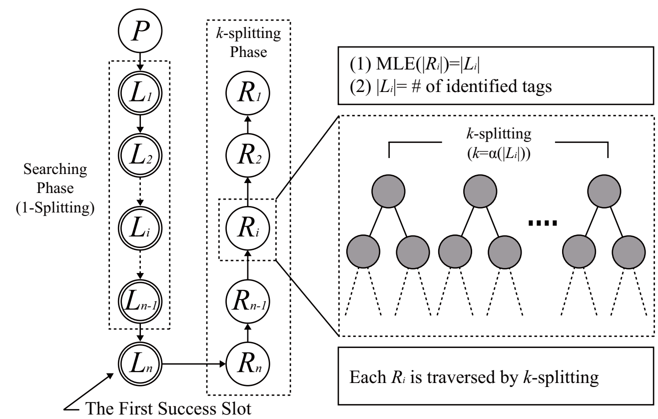

Fig. 1. A tree traversal path of FTTP.

In the rest of this letter, we introduce a fast tree traversal protocol (FTTP) that allows us to minimize the identification delay, by selecting an efficient TTP. Basically, FTTP is based upon BT, and it guarantees a stable tag identification time that is independent of the ID distribution. Adopting depth first search and maximum likelihood estimation (MLE), FTTP predicts the number of tag replies and dynamically adjusts the TTP in order to avoid collision slots.

II. Fast Tree Traversal Protocol

We define $k-splitting$ as the procedure in which tags are allocated to k groups, each of which is traversed by BT. We name k the splitting factor. Note that BT is an example of 1-splitting, because it performs traversal from the root node. FTTP consists of two phases: searching and k-splitting. Tags are traversed by 1-splitting in the searching phase. This phase is terminated when the first success slot occurs. Fig. 1 shows TTP of FTTP, where L_n corresponds to the first success slot. In the k-splitting phase, FTTP sequentially traverses R_n, R_{n-1} ,$\cdots$, R_1 with k-splitting. In each visit, k is dynamically adjusted to minimize the identification delay.

In order to choose the best k value, we analyze the identification delay of k-splitting. The expected delay $S_{k|m}$ to identify m tags with k-splitting is

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$$S_{k|m} = \begin{cases} T_{idle} & k{=}1, m{=}0 \\ T_{succ} & k{=}1, m{=}1 \\ \frac{1}{2^{m-1}-1}\left(2^{m-1}T_{coll}+\sum_{i=0}^{m-1}\binom{m}{i}S_{1|i}\right) & k{=}1, m{>}1 \\ k \cdot T_{idle} & k{>}1, m{=}0 \\ \sum_{i=0}^{m}\binom{m}{i}\left(\frac{1}{k}\right)^{i}\left(1-\frac{1}{k}\right)^{m-i}\left(S_{1|i}+S_{k-1|m-i}\right) & k{>}1, m{>}0 \end{cases} \quad (1)$$

where T_{idle}, T_{succ} and T_{coll} are the durations of the idle, success and collision slot, respectively. Given $S_{1|0}$ and $S_{1|1}$, for $k \geq 1$ and $m > 0$, $S_{k|m}$ can be obtained by bottom-up dynamic programming. $S_{k|m}$ forms a weighted sum of T_{coll}, T_{idle} and T_{succ}. Since the weight factor of T_{succ} in $S_{m|k}$ is always m, $S_{m|k}$ depends on the term of T_{coll} and that of T_{idle}. Let k^* denote the optimal splitting factor. Fig. 2 shows the k^* values as a function of m and γ, where $\gamma = T_{idle}/T_{coll}$. We can observe a linear relation between m and k^* when γ is fixed. We define $\alpha(m)$ as a function which returns the approximated k^* values. The detail of $\alpha(m)$ is described in section IV. The value of γ is determined by the air interface standards and is a fixed value. Therefore, when m is given, k-splitting with k = $\alpha(m)$ is a simple and smart guideline for fast tag identification. Furthermore, since $\alpha(m)$ can be derived before runtime, the reader need not do a complicated computation.

However, since the exact value of m is unknown, we need an estimation method. Let $|\cdot|$ denote the number of tags in a group. For $i = 0, 1, \ldots, n$, the tags in R_i are identified after those in L_i. Therefore, when R_i is visited by FTTP, $|L_i|$ is already given. Since estimating $|R_i|$ involves binomial parameter estimation, the MLE value of $|R_i|$ is $|L_i|$ [4]. FTTP exploits $\alpha(|L_i|)$-splitting when each R_i is visited. Otherwise, 1-splitting is used.

FTTP can be implemented with a slight modification to BT. To determine the splitting factor k, the reader needs to maintain two counters: group counter (GC) and backtracking counter (BC). GC counts the number of unidentified tag-groups and BC records the number of unvisited tag-groups generated before the first tag is identified. Because GC is already used in BT, BC is additionally needed. If their values are the same, k is calculated and transmitted to the tags, and BC decreased by 1; otherwise, k is set to 1. Each tag requires replacement of its pseudorandom binary number generator with the pseudorandom number generator (PRNG) which generates a random integer number within the range [0, k]. Note that this kind of PRNG is already used in aloha-based protocols.

III. Performance Analysis

Let D_m denote the expected delay to identify m tags with FTTP. D_0 is T_{idle} and D_1 is T_{succ}. For $m > 1$, D_m can be obtained by

$$D_m = T_{coll} + \frac{1}{2^m}\left(T_{idle} + D_m\right) + \sum_{i=1}^{m}\frac{1}{2^m}\binom{m}{i}\left(D_i + S_{\alpha(i)|m-i}\right). \quad (2)$$

Since the number of tags is larger than 1, a collision occurs and occupies T_{coll}. After the collision, the tags are split into two

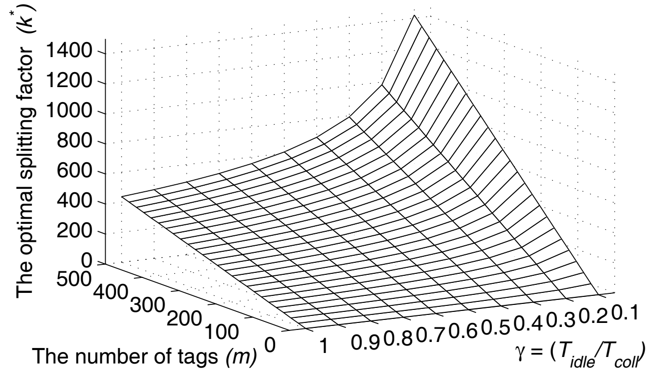

Fig. 2. Relations among the optimal splitting factor k^*, the number of tags m and γ.

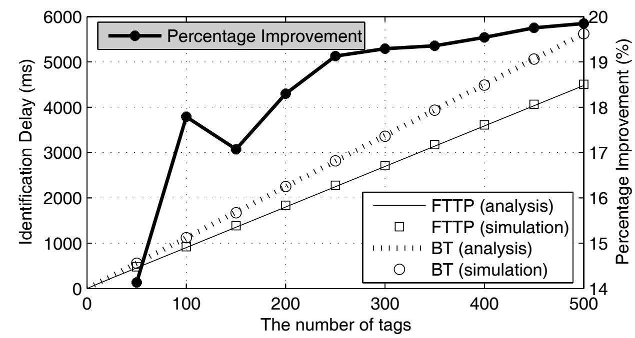

Fig. 3. Identification delay versus the number of tags; comparison of simulation and analysis.

groups. The second term means that the first subgroup causes an idle slot. The last term corresponds to the case where the first subgroup includes i tags and the other one has $m-i$ tags. We can rearrange eq. (2) to solve for D_m.

$$\begin{aligned} D_m &= T_{coll} + \frac{1}{2^m}\left(T_{idle} + D_m\right) + \frac{1}{2^m}\left(D_m + S_{\alpha(m)|0}\right) \\ &\quad + \sum_{i=1}^{m-1}\frac{1}{2^m}\binom{m}{i}\left(D_i + S_{\alpha(i)|m-i}\right) \\ &= \frac{1}{2^m-1}\Big\{T_{coll} + \left(\alpha\left(m\right)+1\right)T_{idle} \\ &\quad + \sum_{i=1}^{m-1}\frac{1}{2^m}\binom{m}{i}\left(D_i + S_{\alpha(i)|m-i}\right)\Big\}. \end{aligned} \quad (3)$$

Because D_0 and D_1 have already been obtained, D_m can be solved by bottom-up dynamic programming.

IV. Performance Evaluation

We have developed our own discrete event simulator to perform extensive simulation studies. FTTP, BT, QT, and Smart Trend Traversal (STT) [1] protocols are implemented. Each experiment is continued until the reader identifies all tags. All experimental results are averaged after 500 iterations with varying random seeds. The simulation parameters are extracted from ISO-18000 type B [2]. We use a uniform distribution model to generate the tag IDs, where the ID length is 64 bits. To calculate the accurate slot duration, most of the

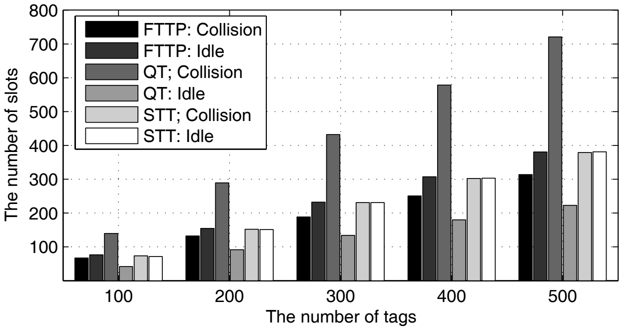

Fig. 4. Collision slots and idle slots consumed to identify all tags.

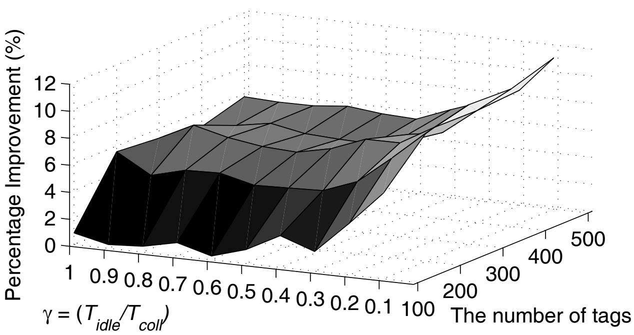

Fig. 5. Improved performance of FTTP when compared with STT.

physical parameters such as the preamble detect, preamble, transmit-to-receive turnaround time, and receive-to-transmit turnaround time are considered. The duration of each slot is as follows: in case of BT, it is 4210 μs for the success and collision slots and 2210 μs for the idle slot; In FTTP, due to the extended commands including the value of splitting factors, a delay of 200 μs is associated with each slot from BT. According to the parameters; γ is set to 0.5465 (= 2410/4410). Using γ and eq. (1), we obtained the k^* values. By linear least squares regression, the α function used in the performance analysis and evaluation is given by

$$\alpha(m) = \lceil 1.1645m + 0.1162 \rceil. \tag{4}$$

In Fig. 3, we show that our analytical and simulated results correspond to each other for FTTP, and deal with each in turn for BT. The right-hand sides of the graphs show the percentage improvement of FTTP on identification delay. FTTP outperforms BT by up to 14-20%. We also compare the performance between FTTP, QT, and STT. Since slot duration is not identical for FTTP and QT-based protocols, we first observe the number of slots. Fig. 4 depicts the number of slots consumed by each protocol. Interestingly, FTTP generates fewer slots than QT and STT in collisions. To show the percentage improvement, we calculate the identification delay of STT, varying γ from 0.1 to 1. As shown in Fig. 5, FTTP outperforms STT by up to 11%.

Although there is no great improvement, the following points are remarkable. Without exploiting the sequential arrangements of tags, FTTP is capable of finding a smart TTP like STT. While STT does not consider the slot duration, FTTP determines its TTP considering γ. Therefore, the percentage improvement increases with decreasing γ. Moreover, since FTTP does not use an ID prefix, its slot durations are shorter than those of the QT-based protocols and its performance is independent of the ID distribution. Considering the fact that the slot duration used in STT is inevitably longer than that used in FTTP, this is a very encouraging result.

V. Conclusion

In this letter, we proposed a novel tree-based tag collision arbitration protocol, viz., FTTP, which minimizes the identification delay. FTTP estimates the number of replies and split tags into several groups in order to reduce collisions. By inheriting BTs functionality, FTTP avoids the shortcomings of the QT-based protocols. We derived a performance analysis between FTTP and BT. The simulation results proved that FTTP outperforms the other extended tree-based protocol as well as the conventional ones.

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