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RESEARCH ARTICLE

Electrica 2019; 19(2): 182-192

Performance Analysis of Tree-Based Tag Anti-Collision Protocols for RFID Systems

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Cite this article as: Yüksel ME, Fidan H. Performance Analysis of Tree-Based Tag Anti-Collision Protocols for RFID Systems. Electrica, 2019; 19(2): 182-192.

ABSTRACT

In today's fast-changing competitive environment, companies and organizations need to develop their services, applications, and business processes continuously in order to benefit more from time and resources. Radio Frequency Identification (RFID), as one of the technological innovations, is an auto-id technology that enables many new application domains in diverse scientific fields and provides important opportunities to build efficient industrial systems. It is capable of identifying, locating, tracking and monitoring objects, and offers companies and organizations important advantages to develop efficient and successful business applications. In RFID systems, tag identification is a critical process. However, tag collisions occur when multiple tags transmit their IDs to a reader simultaneously, and thus affect the stability of the RFID system. Therefore, a powerful tag anti-collision mechanism is required to accelerate the tag identification process while minimizing the collision effects. In this paper, we presented a performance analysis of some of the tree-based tag anti-collision protocols (binary tree, query tree, adaptive binary tree, and adaptive query tree) to evaluate the tag identification process for the RFID system in an IoT environment. In our experiments, we observed that adaptive tree-based tag anti-collision protocols have better performance than the binary tree protocol and the query tree protocol.

Keywords: RFID, IoT, RFID tags, anti-collision, tag identification, identification delay, communication overhead

Introduction

Radio Frequency Identification (RFID) is a wireless automatic identification (Auto-ID) and data gathering technology that gives the opportunity to track and monitor objects by using tags that carry information (Figure 1). The main feature of RFID technology is its ability to identify, locate, track, and monitor objects without a clear line of sight between the tag and the reader [1, 2].

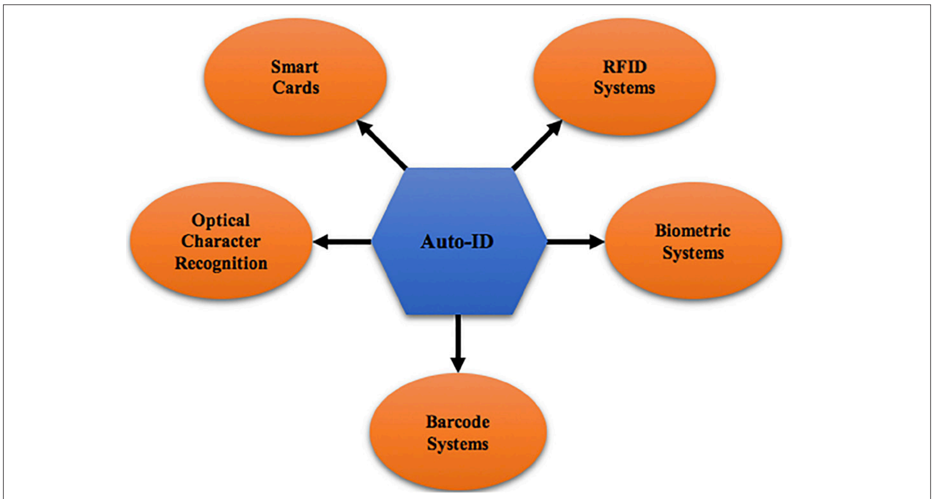

Figure 1. Auto-ID technologies

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Received: 17.05.2019

Accepted: 05.07.2019

DOI: 10.26650/electrica.2019.19030

The architectural structure of RFID is much more similar to smart cards that contain microchips. As in smart card systems, object-related information (data) is stored in an electronic data storage device which is called RFID tag consisting of a microprocessor and an antenna [2]. RFID tags can be active or passive. Active tags use a battery to supply power. On the other hand, the power of passive tags is provided by signals from the reader. The data exchange between the tag and the reader and the tag and other tags is performed by an electromagnetic field or wireless communication (radio frequencies) [3, 4].

In an RFID system, the data communication and the energy transfer occur between the reader and the tag. The electromagnetic waves emitted by the reader meet the antenna and activate the microchip inside the tag. The microchip modulates the received signals and sends it back to the reader via the tag antenna [1, 2]. Figure 2 illustrates a basic RFID system and provides an information about how it works. In an RFID system, tags are detected by the reader when they enter the reader's interrogation area. The tags send their data to the reader through RF signals. The reader converts these signals into digital data. The information generated by the RFID reader is transmitted to the related services/units within the system via middleware, software, controllers, servers, and network devices [1, 2, 4-6].

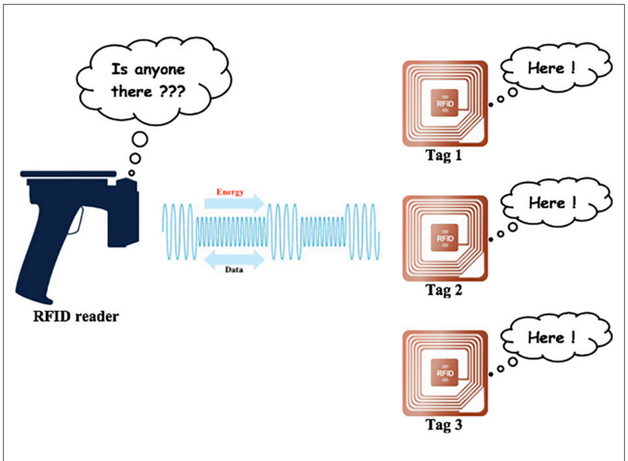

Figure 2. Data communication in an RFID system

RFID systems can be divided into two major groups, as mobile and immobile applications. Immobile RFID systems include RFID readers, antennas, hosts, servers, middleware, and external units such as light and sensors. These systems are also called RFID gates. In these systems, readers serve as gates, receive information from tagged objects and send these information to servers or controllers. Mobile systems employ wireless communication to gather data and monitor objects. They are similar to fixed systems due to the RFID system structure. They provide advantages such as data gathering and managing, reading/writing ranges and communication technologies. Reading/writing data from/to RFID tags is done by radio frequency. Passive tags are activated by the energy that is generated by the RFID readers, and send their own information to the readers. RFID readers receive information and transfer this information to related units (controllers, servers, database systems) in an IoT ecosystem [1, 2, 7, 8].

The differences in data communication techniques, the production and the application purposes of RFID show why these systems are very special applications. If the advanced features of RFID systems, the different application options are well understood and examined, strategies can be developed for how these systems can be used efficiently in enterprises or institutions [9, 10].

Figure 3 shows the various features of RFID systems that can be used to differentiate one RFID application from another. Hence, the basic design criterias and parameters in RFID system features can be stated as capacity of data read, the distance of variable read, tag durability, life expectancy, potential barier, tag diversity, capcity of data storage, data flexibility, etc. Some of these features are briefly explained as below [1, 4]:

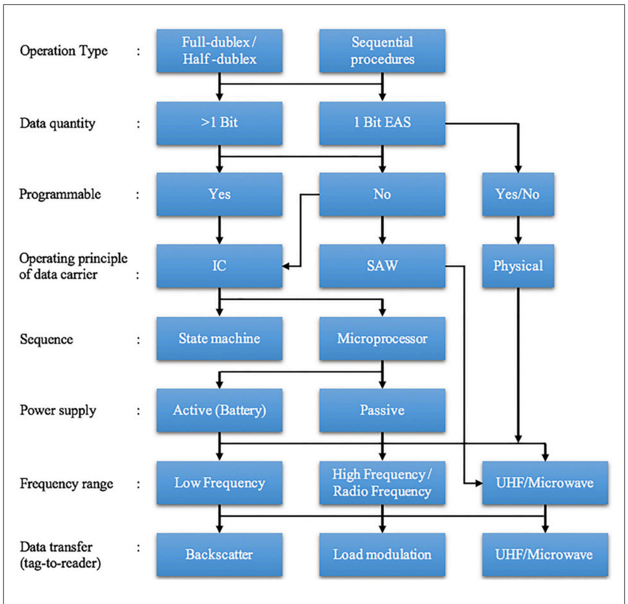

Figure 3. The various features of RFID systems [4]

Operation frequency: When selecting a frequency for an RFID system, the characteristic of several available frequency ranges must be taken into account. The availability of applicable frequencies and frequency bands in the operating area of the system has a significant impact on the system parameters [1, 4].

Modification: The ability to change or to write data to the tag.

Potential barriers: Factors that prevent the tag to be read properly.

Data security: It is the ability to encrypt data in the tag. In RFID applications, security requirements such as encryption, identification, authorization, etc. must be fully evaluated at the implementation stage [1, 4, 10].

Tag memory capacity: The amount of useful data the tag can store. The chip size of the data storage is specified by capacity of the memory. So, encrypted read-only data storages (tags) are used in price-oriented mass applications with low local information requirements. However, only one object description can be identified by using such a data carrier. Additional data are stored in the central database of the host computer. If the data needs to be rewrite to the tag, tags which have EEPROM or RAM memory technology can be used [1, 4, 10].

Cost: The costs of basic and auxiliary devices in the system needed.

International Standards: The ability to include a set of open standards accepted by many manufacturers and users is that it can meet technology-based global data and application standards.

Range: Range concerns whether the tag requires a line of sight for reading and how much remote signal it collects. The distance between tags should be set so that there is only one tag at a time in the reader's query area. The range required in an application depends on several factors such as the correct tag position, the minimum distance between many tags and the speed of the tag in the reader's query area [1, 4].

Instant number of readings: Data of an object should not be read only one time. Multiple data should be allowed to be read at a specific time. The maximum read/write distance and the time spent by the tag in the reader's query area determine the speed at which tags are associated with readers. The time and distance required to define objects, the time spent in the interrogation area at the maximum object passing speed, and the range required for the RFID system should be designed to be sufficient to transmit the needed data [1, 4].

Operational lifetime: The length of time that the tags used in an RFID system are readable.

Multiple-access and Anti-collision in RFID Systems

The processing of RFID systems usually involves a situation where multiple tags are present at the same time in the query region of a single reader. There are two main communication protocols as broadcast and multiple access in such a system. Broadcast communication is applied to transmit data from the reader to the tags. The data sent by the reader is taken simultaneously by all the tags in the query area of the reader (Figure 4). This comminication protocol can be imagened as the simultaneous reception of a news program transmitted by a radio station to the hundreds of radio receivers [1, 11].

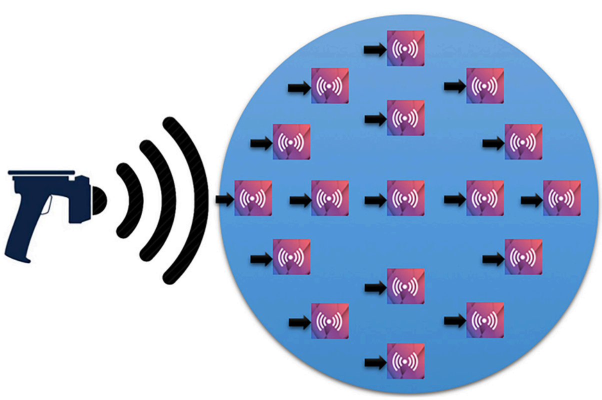

Figure 4. Broadcast communication

The multiple access protocol involves the transmitting data to tags in the query area of the reader (Figure 5). In multiple accesses protocol, many tags try to transfer data to a reader simultaneously [12].

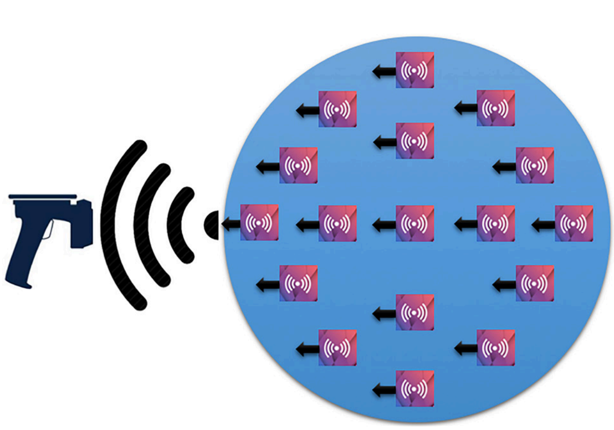

Figure 5. Multiple access

The communication channels have specific channel capacities that are specified by the maximum data rate of the channel and the usability period. The channel capacity must be divided between individual receivers to transmit the mutual data without collision from the tags to the reader. For example; In an integrated passive RFID system, only the receiver portion in the reader can be used by all tags in the query area, as a common channel for data transfer to the reader. The maximum data rate is calculated via effective bandwidth of the antennas which are on the tag and the reader [1, 4, 7].

The multiple access problem is one of the most studied issues in the radio technology researches such as satellites and mobile technologies. The problem is that many participants attempt to access a single satellite or base station. So, it has crucial importance to differentiate individual participant signals. Although several protocols have been developed, mainly there are four multiple access protocols such as Space Division Multiple Access (SDMA), Frequency Domain Multiple Access (FDMA), Time Domain Multiple Access (TDMA), and Code Division Multiple Access (CDMA). These protocols are based on the assumption that there is a continuous flow of data from the participants. When a channel capacity is divided for communication, the channel remains divided until the communication is over [1, 7, 8].

The tags used in RFID systems are characterized by short-term activities in which unequal length gaps are entered. Tags are a particular problem in almost all RFID systems because, a tag cannot immediately be detected among the other tags in the reader's query area. The tag in the query area of a reader needs to be verified, read and written within a few milliseconds. After this process, the tags may not enter into the reader's query area for a long period of time. However, this situation does not mean that the multiple access protocol is not necessary for such an application. It should be considered that there are more tags of the same type at any location and that they are detected by the reader antenna. The activities on the transmission channels between the reader and the tag have high bursting factors. So, a packet access protocol must be used. The channel capacity should be divided only when really necessary. A powerful multi-access protocol can provide succesfull tag recognition by selecting the correct label without significant delay [1, 9, 10].

The implementation of the multiple access protocol in RFID systems contains some difficulties for the tag and reader. The implementation procedure should reliably prevent the collision that causes the unreadable of the tag data by the reader. Also, this process should not lead a noticeable delay. In RFID systems, the procedure that facilitates multiple access without collision is called as anti-collision protocol. Anti-collision protocols can be classified in two general groups as probabilistic approach protocols (ALOHA based) and deterministic approach protocols (tree based). In ALOHA based protocols, each tag attempts to send its own identification data (ID) at choosen time randomly. Although ALOHA based protocols reduce the probability of tag collisions, they cannot abolish completely [13]. So, They create a crucial problem, such as the failure to identify a particular tag for a long time that is known as starvation problem. Tree-based protocols create a conceptual binary tree during the tag recognition process. In this approach, the tags are divided into two subgroups at once and tried to recognize the subsets individually [14]. All tags in the reader's query area can be recognized by dividing to the subsets until each tag series has a single tag. Tree-based protocols do not lead to starvation problem, but delays in identifying tags are longer compared to ALOHA based protocols [15].

Tree-based Tag Anti-collision Protocols

Tree-based protocols perform the tag recognition within read cycle units. A query has been transmitted in a read cycle to the tags by the reader, then one or several tag send the IDs. The collisions cannot be perceived by the passive tags. However, the reader can detect the collisions among the responses of the tags. The reader determines the content of the query according to the result of this detection in the next read cycle [10, 13]. The tag decides whether transmit data or not when it receives a query from the reader. If a single tag transmits data only in one read cycle, the reader can recognize the tag successfully [10, 16].

In tree-based protocols, the reader recognizes all tags within the query area during a recognition frame consisting of several read cycles. The reader attempts to recognize a group of tags that transmit the data in the same read cycle [10, 13]. If there is more than one tag in the group, tag transmissions cause collision. When a collision occurs, the binary tree algorithm divides the tags in the group into two subsets by using tag IDs or random binary numbers [10, 16]. Then, the reader attempts to identify the two subgroups in the same frame individually. Tree-based protocols attempt to recognize all tags within range of the reader by continuing the division until a single tag remains in each group [10, 17].

A recognition frame in tree-based anti-collision protocols can be represented by different types of tree structures shown in Figure 6. Each node in the trees corresponds to a reading cycle. The numbers in the nodes are the count of tag transmissions in the read cycle. Depending on the number of tag transmissions, the read cycles can be seen in three cases [13, 16, 17]:

Idle cycle: There is no transmission attempts. An unnecessary recognition delay occurs. It does not cause the reader not to notice a tag.

Readable cycle: A transmission attempt occurs and the reader successfully recognizes the tag.

Collision cycle: More than one transmission attempt are seen and collision occurs. The reader cannot recognize any tags. The collision cycle delays tag recognition. The reader sends a query

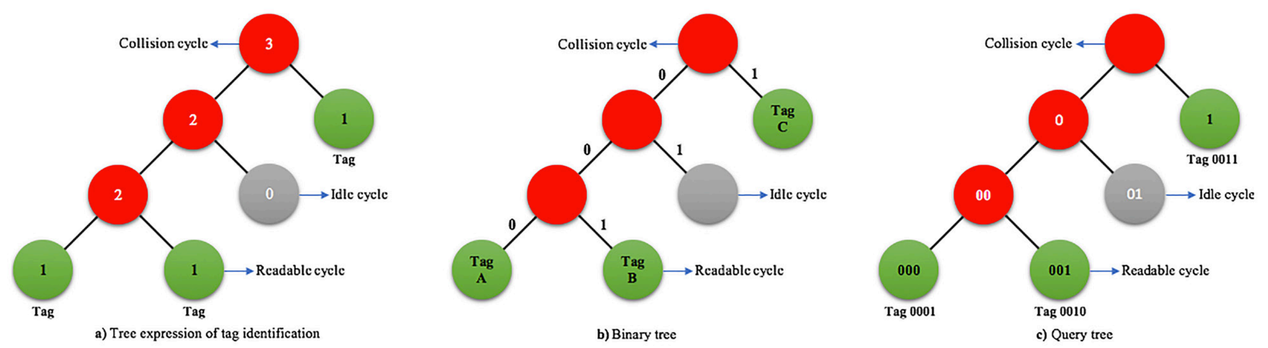

Figure 6. Tag identification in tree-based protocols

to all tags and performs segmentation of the tag set, including colliding tags [18].

Since a group is divided into two subsets in the recognition frame tree, the node of the collision cycle has only two sub-nodes that called leaf node. In tree-based protocols, collision cycles correspond to the nodes while readable cycles or null cycles correspond to leaf nodes. The tag recognition is a search process that to realized on the roots of the tree to find nodes of readable cycles. The performance of the recognition process depends on how effectively the group divides and how efficient the search works [10, 17].

Binary Tree Protocol

The binary tree protocol uses random binary numbers generated by collision of tags for the division procedure. The tag has a counter value loaded with 0 at the beginning of the frame. When the counter value is 0, the tag transmits the own ID. All tags create a group at the beginning of the frame and they transmit the data at the same time. The reader informs the tags about the collisions by creating a query. According to the reader's query, all tags change their counter values [19]. When the transmission of a tag causes collision, the tag selects a random binary number. The group is divided into two subgroups by adding the selected binary number to the counter value. When a collision occurs, the non-collision tag that counter value is not 0 increases the counter value by 1. If the reader's query does not indicate a collision, all tags reduce the counter values by one. The tag understands that the transmission is successful and that there is no collision. The tag that a reader does not recognize does not transmit any signals until the frame is terminated [16-19]. Figure 7 shows the tag recognition process in the binary tree protocol, and the numbers next to the lines indicate binary numbers randomly selected by the colliding tags. The reader also has a counter to end the frame [13]. The reader loads the counter value with 0 in each frame. The reader's counter value indicates the number of tag sets that are not yet recognized in a frame. If a collision occurs, the reader adds 1 to the counter value because of the increasing the number of tag sets that the reader should recognize. Otherwise, the reader decreases the counter value by 1. When the reader's counter value is less than 0 (counter value<0), the reader terminates the frame [10, 13, 17].

The binary tree protocol uses a random number generator. The RFID reader emits a signal and prompts the tags to generate random numbers. Each tag produces 0 or 1 and adds this value to the counter and sends a reply to the reader. The reader groups the tags based on the number values in the tags' counter. Whenever any collision occurs, the tags causing the collision increase their counters again by generating a random number. This process continues until each tag in the tree remains alone on a leaf node. The tag, which becomes readable at the end of the process, transfers its contents to the RFID reader. Binary tree protocol gives better performance even most of the tag IDs are the same. However, if tags that generate random numbers produce the same number continuously, the long reading time can be seen in this protocol [1, 10, 19].

Query Tree Protocol

The query tree protocol uses tag IDs to subdivide tags. The reader sends a query containing a bit series to the tags. Tags, which the IDs start with this bit series, send the ID information to the reader in response. The first tag, which has equual ID bits with the bit series, responds by passing the ID to the reader. If there is a collision while receiving the answers, the reader will send the query to the next reading cycle by increasing the length of the bit series by 1. [1, 20]

In the query tree protocol, the reader has the Q queue for the bit series. At the start of the frame, Q is started with two strings which have 1 bit length and values are 0 and 1. The reader removes a bit series from Q and passes only one query every time. If the tag responses collide, the reader adds two series which are 1 bit long to the Q. All tags are recognized by expanding the query until a response or no response is received [5, 10, 13]. Figure 8 shows the tag recognition procedures in

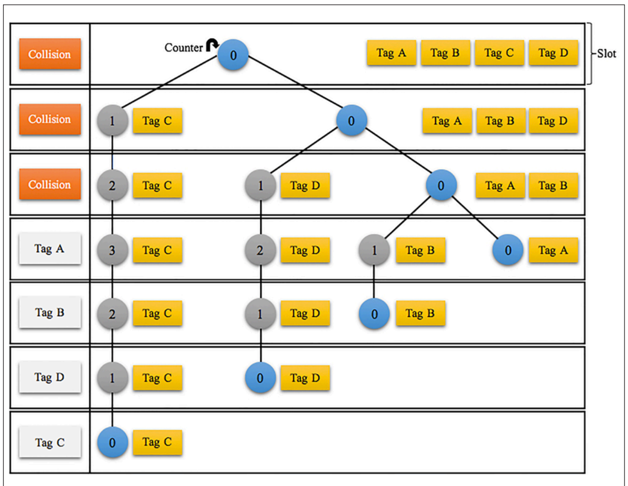

Figure 7. Tag identification using the binary tree protocol

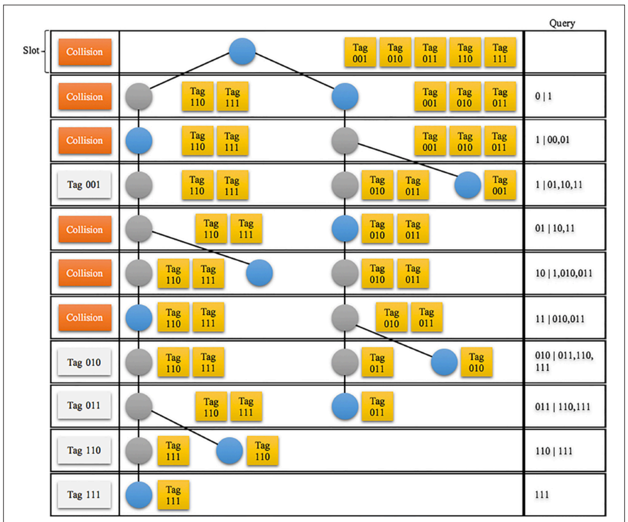

Figure 8. Tag identification using the query tree protocol

the query tree protocol. The number inside the nodes defines the query that the reader transmits [10]. The reader first sends a signal to the tags in the query area. With this signal, tags which the first bit is 1, are queried. The tags compare their IDs with the query, and the appropriate ones send the response to the reader. The tags are then grouped according to their IDs and the query tree is divided into two subnodes. These operations are repeated on each node. Thus, each tag is placed on a node.

For example; If the tag responses of the q1q2. . . qx query (qi € {0, 1}, 1 <x <b, and b have the number of bits in the tag ID) collide, the reader uses two queries longer than 1 bit in subsequent read cycles as (q1q2 . . . qx0) and (q1q2 . . . qx1) [17]. The tag group that matches (q1q2.. qx) is divided into two subgroups. One of the subgroups is the tag group that matches (q1q2 . . . qx0), the other is the tag groups matching (q1q2 . . . qx1) [17]. Because each tag has a unique ID as a result of the query, tags can be queued according to the query string. The reader will read all the tags by contacting the tags in the ID queue one by one. If there is a collision again, the reader will query again by adding 1 bit to the query parameter. All the tags will be read with this process that continues until the response is received [10, 17].

Compared to the binary tree protocol, the query tree protocol performs simple operations on tags. The query tree protocol is also known as the non-memory protocol because the tags only need to hold the ID information [21]. The shortness of the delay time in this protocol varies depending on the similarity of the IDs of the tags. If the majority of tag IDs are the same, reading with this method may take a long time. The delay time increases as the number of similar IDs increases [1].

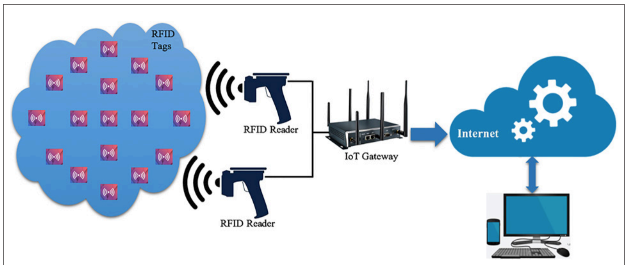

Figure 9. System architecture

Adaptive Tree-based Protocols

These protocols are improvements of tree-based protocols. They use the information provided by the last frame in the reader to avoid tag collisions. They have fast tag identification characteristics by decreasing not only collisions but also unnecessary cycles. They suppress the occurrence of collisions, shorten the total delay for tag identification, and preserve low communication overhead, while still identifying all tags [13]. In these protocols, RFID readers accomplish tag identification processes repeatedly, and RFID tags are classified into three groups based on the tag mobility (i.e, object tracking and monitoring): staying tags, arriving tags, and leaving tags. There are two types of adaptive splitting protocols: adaptive binary splitting [21, 22] and adaptive query splitting [23, 24]. In adaptive binary splitting, tag identification process is started from only readable cycles of the last frame and random numbers are used to split tag sets. In adaptive query splitting, tag transmissions are controlled by reader interrogations analogous to query tree. Tags are memoryless and store only their own IDs. To eliminate collisions between staying tags, the reader does not transmit queries that multiple tags responded in the last frame [13, 16, 17].

System Model

We consider an RFID-based tracking system for mobile objects in an indoor environment. As shown in Figure 9, the system contains a reader and passive UHF tags. Tags enter and leave the reader interrogation area. When tags are not inside the reader interrogation area, they are all passive. Tags are only activated when they are in the reader interrogation area. We assume that the tags move with a relative low speed (serious packet loss can be occured when the tags move with a high speed, resulting that several tags cannot be detected), and the reader can perform tag identification process repeatedly.

Tag identification is a dynamic and continuous process consisting of reader request and tag response. The primary consideration when selecting the RFID tags is to find the optimal balance between the tag size and the read range. The right read range depends on the distance between the reader and tags. Figure 10 illustrates the data tranmission in a basic RFID

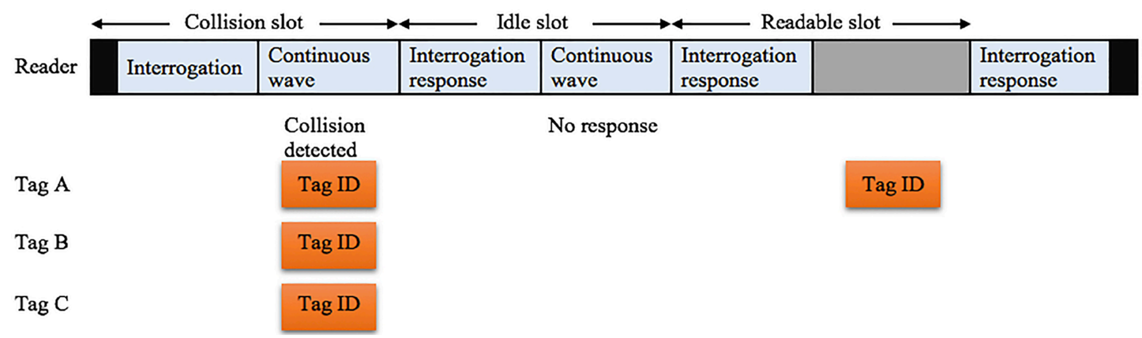

Figure 10. Tag identification process

system. Based on the number of tag ID transmissions in a query period, the tag reading process is divided into three parts on the reader side:

- Readable slot: Just one tag responds to the reader. The reader successfully recognizes the tag.
- Collision slot: Reader receives signals but cannot recognize any tag. Two or more tags respond to reader simultaneously. Tag identification process fails depending on the collision.
- Idle slot: The reader does not receive any tag signal. Unnecessary increment of the identification delay occurs.

In our system, the reader can recognize multiple tags. When tags enter the reader interrogation area, all that they have to perform is to become active and respond with the data corresponding to the reader signal. The communication between the tags is impossible, and the tags cannot decide whether the channel is busy or not. The medium is shared by two or more tags, and thus collisions occur at the reader side when these tags transmit data simultaneously. Since collisions make the collided signals be retransmitted, the power consumption of the tags and the time elapsed for recognizing the tags increase. Therefore, an efficient tag anti-collision scheme with fast identification and low computational complexity is required.

Performance Analysis

We evaluated the performance of the tree-based tag anti-collision protocols: binary tree, query tree, adaptive binary tree, and adaptive query tree. These protocols employ the binary search tree to identify the RFID tags. We make use of the methods presented in [1, 10, 13]. We take into account the following aspects in order to analysis the tag identification process [1, 10, 13]:

- Number of collisions: Collisions prevent the tag identification and increase the tag power consumption.
- Tag identification delay: Total delay required for the reader to recognize all tags in its own query area.
- Number of idle cycles: This affects the tag identification delay.
- Tag communication overhead: The average number of bits in a frame. It affects the tag power consumption.

We assume that T_x indicates tag x, N is the number of tags in our simulation environment, $T_{R,i}$ denotes the set of tags in the interrogation area of reader R during i^{th} frame F_i, and $|T_{R,i}|$ is the number of tags in set $T_{R,i}$. In order to take tag mobility into account, we classify the tags into three groups: remaining tags (stay inside the interrogation area), arriving tags (pass through the interrogation area), and leaving tags (leave the interrogation area). We can give the following definitions for our system model:

- Frame F_i: The i^{th} identification process that a reader executes. It is the period from the moment the reader starts identifying tags in its interrogation area to the moment it completes the tag identification.
- Slot: The duration reader R sends an interrogation signal to tags and tags send their IDs to reader R. It can be idle, readable, or collision.
- T_x:T_x € $\{T_{R,i} \cap T_{R,i}\}$, T_x is a remaining tag.
- T_x:T_x € $\{T_{R,i+1} - T_{R,i}\}$, T_x is an arriving tag
- T_x:T_x € $\{T_{R,i} - T_{R,i+1}\}$, T_x is a leaving tag.

Table 1 shows the simulation setup. We assume that there are 250 tags attached to the objects moving at a constant speed in an area of 50 x 50 m^2. Tag ID length is 128 bits. Tag IDs are randomly generated for every simulation scene. At the start of the simulation, all tags are randomly distributed in the simulation environment. The reader is placed in the middle of the simulation area. The interrogation range of the reader is 5 m. Since the reader's interrogation range is 5 m, some tags enter and leave the interrogation area. In order to evaluate the system performance, we considered several factors such as number of tags, tag ID similarity, tag mobility, tag communication overhead, tag identification delay, number of readers, reader interrogation area, tag moving speed, number of collisions, number of idle cycles, and tag stationary probability.

Table 1. Simulation setup

Parameters	Values
Simulation area (m^2)	50 x 50
Tag ID (randomly generated)	128 bit
Number of tags	250 (max. 3000)
Tag moving speed (m/frame)	1 (max. 5)
Number of readers	1 (max. 5)
Read range (m)	3 (max. 10)

Tag moving speed indicates the physical distance which a tag moves during one frame. To evaluate tag identification process, we define the moving speed for a tag as follows [10, 13]:

$$v(T_x) = d_{Tx}(t)/F_{prtcl}(t) \quad (1)$$

- t: represents a specific time interval $[t_i, t_{i+1}]$.
- $d_{Tx}(t)$: the distance that T_x moves in t.
- $F_{prtcl}(t)$: The number of frames that the anti-collision protocol executes in t.

Figure 11, 12, and 13 present the effect of varying the number of tags in the reader interrogation area. When the number of tags increases, collisions take place more often and tag identification delay increases. Binary tree and query tree give similar delay results. Small differences in delay between these protocols result from the initial points of the identification process. On the other hand, adaptive tree protocols have shorter identification delay than the binary tree and query tree. In addition, the number of collisions and the communication overhead in adaptive tree protocols is less than the binary tree and query tree [1, 10, 13].

Figure 14 and Figure 15 illustrate the impact of tag ID similarity on the anti-collision protocols presented. Binary tree-based protocols are not affected by tag ID similarity because they do not employ tag ID patterns. On the other hand, since query tree-based protocols use tag IDs to split the tag set, they are affected by tag ID similarity. As the number of identical bit increases, the performance of query tree-based protocols deteriorates. Query tree-based protocols, as compared to binary tree-based protocols, have long tag identification delay and high tag communication overhead because the reader sends all interrogations leading to collisions in every frame and the number of idle cycles increases [1, 10, 13].

Figure 16 shows the impact of tag moving speed for the anti-collision protocols presented. When tags move at low speed, adaptive tree protocols have good performance than the binary tree and query tree. When $v(T_x) = 0$, adaptive tree protocols prevent collisions between remaining tags because they do not allocate more than one remaining tag to a set. When tags have high speed (or move faster), there are some remaining tags and collisions between these tags at the binary tree and query tree protocols hardly occur. In this case, adaptive

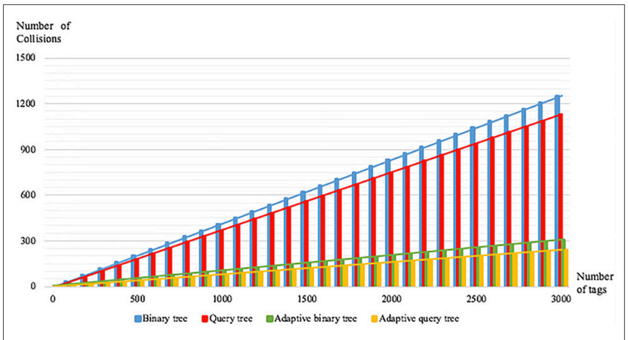

Figure 11. Collisions by the number of tags

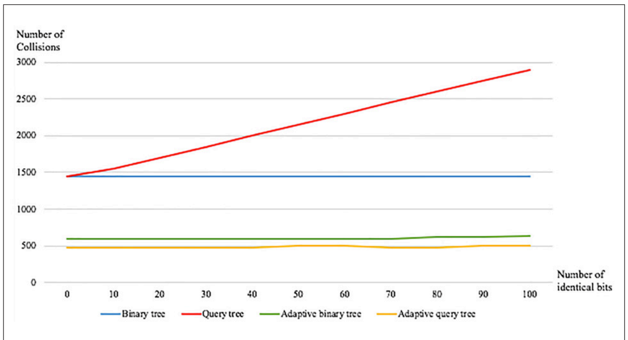

Figure 14. Impact of tag ID similarity

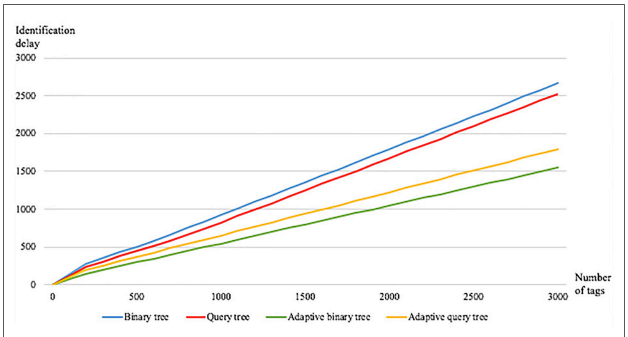

Figure 12. Identification delay by the number of tags

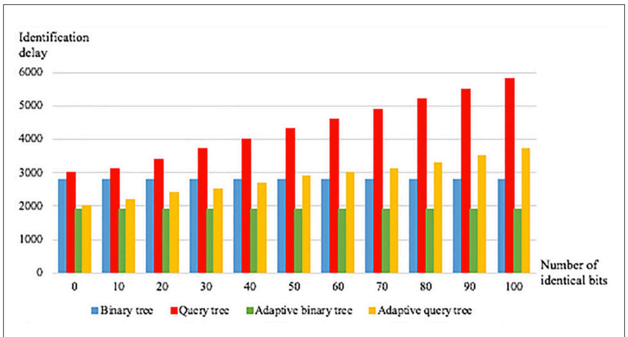

Figure 15. Identification delay by tag ID similarity

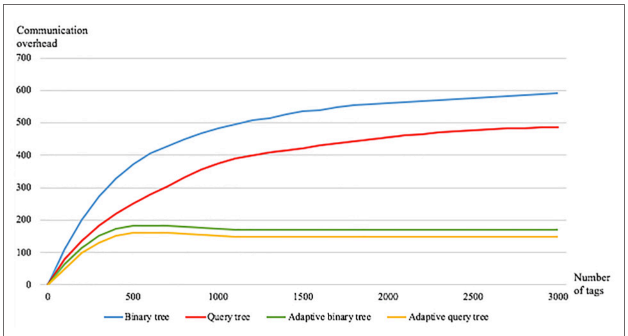

Figure 13. Communication overhead by the number of tags

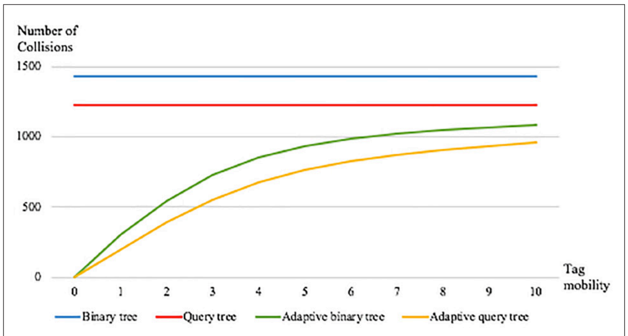

Figure 16. Impact of tag moving speed

tree protocols show performance similar to the binary tree and query tree [1, 10, 13].

Discussion

In today's rapidly changing competition environment, companies and organizations need to renew their services and communication techniques, change or revise their current business methods in order to benefit more from time and sources. In addition, automatic identification, object tracking and monitorig, data gathering and management technologies are always required for companies and organizations to develop applications and manage bussiness processes. Therefore, continuous innovations in data communication and information technology have lead to the development of new IoT systems using RFID [1].

In RFID system designs, it is aimed to build, collect, and manage dynamic information without any human contribution in real-time. Furthermore, it is required to employ more faster, more efficient, more secure, wide capacited communication technologies to instantly access dynamic object information in larger geographical areas without any limitations, to track and monitor objects, and to route the information associated with objects to the related systems. Therefore, the integration of RFID systems with IoT in the context of data gathering, management and analysis can lead to significant improvements in adaptability, sustainability, and efficiency for the industrial world including firms, manufacturers, retailers, customers, service providers, rule-makers, and end-users [1].

In RFID systems, data transmissions between readers and tags cause collisions because these devices use the same frequency band for mutual data communications. We can classify collisions into two categories: reader collision and tag collision. In a reader collision, when neighboring readers query a tag at the same time, reader signals collide and the tag cannot process any signal. In a tag collision, when multiple tags send their IDs to a reader simultaneously, tag signals collide and the reader cannot identify any tag. Since collisions lead to identification delay and communication overhead, they influence the RFID system's performance and stability [1, 10, 13].

Tag anti-collision protocols can be categorized into two groups: deterministic approaches (tree-based) and probabilistic approaches (ALOHA-based). ALOHA-based approaches reduce the occurrence probability of tag collisions since each tag attempts to send its ID at a randomly selected time. They have several problems that specific tags cannot be recognized for a long time. They cannot completely prevent the tag collisions and therefore cause the tag starvation problem. Tree-based approaches construct a tree conceptually for the tag identification process. They divide the tag set into two subsets and try to identify the subsets one by one. By dividing until each tag set has only one tag, the reader recognizes all tags in its interrogation zone. Tree-based approaches do not lead to the tag starvation problem. However, they have long tag identification delay as compared to ALOHA-based approaches [1, 10, 13].

Tag mobility is an important factor for RFID applications. We can classify the RFID applications into two groups: mobile and immobile. In immobile systems, deterministic and probabilistic anti-collision approaches can show similar features in terms of tag identification. In mobile systems, the time to recognize all tags in the reader interrogation area is an important factor for an anti-collision protocol's performance. For RFID applications that require continuous observation of tags, adaptive splitting protocols perform better than others, if the tag population has low speed.

Conclusion

In an RFID application, when a reader cannot recognize all tags in its own interrogation zone, data retransmission between the reader and tags is required for successful tag identification. In particular, since the neighboring tags cannot communicate with each other and make a decision on whether the channel is busy or not, tag collisions occur and consequently the collided tags retransmit their IDs to the reader. Tag collisions cause communication overhead, significant delays in data transmission, and critical faults that affect the system functionality and reliability. Therefore, an efficient and effective tag anti-collision protocol must be designed to enable the real-time execution and the fast identification process while minimizing collisions. Consequently, a tag anti-collision protocol used in an RFID application must have the following features:

- A reader must be able to promptly recognize all tags in its interrogation area. In mobile RFID applications such as real-time object tracking and monitoring, logistics and supply chain management, the tag identification process must keep pace with the moving speeds of objects. If the identification process is performed slower than the moving speeds of objects, the reader cannot identify the tags, and the tag starvation problem occurs, and thus the RFID system fails. Since the reader cannot precisely estimate the number of tags and their situations in its query area, the guarantee of identifying all tags should be considered in the development of tag anti-collision protocols.
- Tags must be identified while consuming less energy. In a passive RFID system, a tag's power is limited because its power is supplied by the reader signal. Furthermore, RFID tags have limited memory and low computational capability. Therefore, tag anti-collision protocols have to load the tags with less computational complexity and communication overhead.

Peer-review: Externally peer-reviewed.

Conflict of Interest: The authors have no conflicts of interest to declare.

Financial Disclosure: The authors declared that the study has received no financial support.

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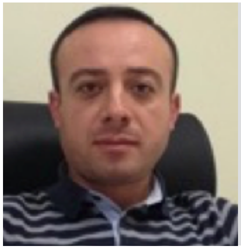

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