

Development of a Dynamic Collision Avoidance Algorithm for Indoor Tracking System Based on Active RFID

Sekyung Han¹, Yeonsuk Choi², Masayuki Iwai¹ and Kaoru Sezaki¹

¹School of Information Science and Technology, The University of Tokyo,
4-6-1 Komaba, Meguro, Tokyo, Japan

[e-mail: arnold@mcl.iis.u-tokyo.ac.jp, {masa, sezaki}@iis.u-tokyo.ac.jp]

²Department of Liberal Arts, Hoseo University
268, Anseo-dong, Cheonan, Chungnam, Korea

[e-mail: changwah@hoseo.edu]

*Corresponding author: Yeonsuk Choi

*Received March 11, 2010; revised June 10, 2010; revised July 21, 2010; accepted August 27, 2010;
published October 30, 2010*

Abstract

We propose a novel collision-avoidance algorithm for the active type RFID regarding an indoor tracking system. Several well-known collision avoidance algorithms are analyzed considering the adequacy for the indoor tracking system. We prove the superiority of the slotted ALOHA in comparison with CSMA for short and fixed length packets like an ID message in RFID. Observed results show that they are not applicable for active type RFID in terms of energy efficiency. Putting these all together, we propose a dedicated collision avoidance algorithm considering the unique features of the indoor tracking system. The proposed method includes a scheduled tag access period (STAP) as well as a random tag access period (RTAP) to address both of the static and dynamic characteristics of the system. The system parameters are determined through a quantitative analysis of the throughput and energy efficiency. Especially, some mathematical techniques have been deployed to obtain the optimal slot count for RTAP. Finally, simulation results are provided to illustrate the performance of the proposed method with variations of the parameters.

Keywords: RFID, collision avoidance, indoor tracking System, anti-collision, localization

A preliminary version of this paper appeared in ICONI/APIC-IST 2009, Dec 17-21, NUSA DUA(Bali), Indonesia. This version is improved considerably from the previous version by including new results and features.

DOI: 10.3837/tiis.2010.10.003

1. Introduction

As the use of wireless devices has become pervasive, many service vendors have started to provide services based on the location of a mobile station. These services mostly provide environmental information such as location of the nearest restaurant. Such GPS based services offer comparably low resolution. Moreover, those services are restricted to outdoor use only, and thus it is difficult to introduce an add-on service with an existing mobile device for indoor environment. Hence, dedicated systems based on active type RFID or infrared (IR) [1][2] are generally employed for indoor localization.

A typical IR based tracking system utilizes existing LAN infrastructure inside a building with dedicated IR beacons. These beacons are usually installed on the ceiling of a room emitting light signal periodically. A badge attached to a mobile entity, say a laptop, receives this signal and determines its own location by reading the ID of the beacon embedded in the signal. Then it notifies the server about its location via the LAN. This system provides comparably higher resolution that is proportional to the density of the beacons. However, its usage is restricted in many ways due to its innate characteristics. First, it cannot cover a wide area because of its line of sight (LOS) propagation that in turn results in many invisible areas [4]. To cover the entire area, there should be many IR beacons incurring higher cost. Second, the badges consume considerable amount of power due to the scheme of the system, and hence inefficient for battery powered mobile entities. In contrast to the system that identifies a tag location by its own transmission, an IR badge should be alert always since the badge should listen to the beacon signal and transmit its position back to the system.

On the other hand, an RFID system can overcome those problems [2][3]. For the RFID system, both the passive and the active types can be considered. A passive type RFID system is employed to identify an asset with a portable interrogator. Since the passive type tags receive power from the interrogation magnetic field, the maximum response range is restricted to a few meters. Due to this short responding range, the passive type RFID is normally inadequate for the purpose of a tracking system. On the other hand, an active type RFID can surmount the defects of the IR and the passive type RFID systems. An active type RFID tag is activated by its own battery, and thus a single base station (a receiver) can cover much wider area than the interrogator of the passive type RFID. In addition, unlike the IR badges, it is quite advantageous in terms of the energy efficiency since an RFID tag can fall into sleep mode except when it is transmitting its ID.

For the aforementioned reasons, active type RFID has become the most popular technology for an indoor mobility tracking system. Nevertheless, due to the wide coverage of the tags, an RFID system suffers from the problem of collision just like other communication systems. So far, many collision avoidance methods have been proposed to resolve the problem in various communication fields. However, most of the active type RFID systems either do not employ the collision avoidance methods at all, or borrow it from other systems without modification. The collision problem, however, seriously degrades the performance, and hence renders the system intractable as the number of tags increases. In this paper, considering the characteristics of the indoor tracking system, we propose a dedicated collision avoidance algorithm for the active type RFID. In sections 2 and 3, the existing collision avoidance algorithms and the features of the indoor mobile tracking system are analyzed. Then we propose our own collision avoidance algorithm with a mathematical analysis in section 4. Finally, simulations are provided to illustrate the performance of the proposed algorithm.

2. Related Work-Existing Collision Avoidance Methods

2.1 Probabilistic Methods

The collision could be avoided if all nodes can exchange the information of when to transmit. However, in most communication systems, packets are generated randomly hence making it difficult to avoid the collisions deterministically. Instead, each node tries to reduce the probability of the collision by randomly selecting the time to transmit. This kind of effort to reduce the collision is called probabilistic collision avoidance method. ALOHA is a typical probabilistic mechanism where each node tries to transmit as soon as they get a packet and if it does not receive an ACK from the party, it retransmits the packet. In this case, the maximum channel utilization is only 17% [4]. On the other hand, slotted ALOHA, an enhanced version of ALOHA, shows the maximum channel utilization of 37% [4]. In this method, each tag synchronizes the beginning of its transmission at a fixed moment called a slot rather than transmitting immediately [5][6]. Since a node can transmit a packet at any moment in pure ALOHA, it can be overlapped with other packets partially. This can yield the entire colliding duration up to two times longer than the packet length. However, if all packets from all nodes are synchronized, that is all transmissions start at the same moment, then the colliding packet duration would be only the length of a packet. However, still there is a problem. In order to implement the slotted ALOHA, all nodes should have a certain mechanism to synchronize with each other. In most cases, this is done by letting the nodes hear a synchronization signal called a beacon. Whenever a node wants to transmit a packet it should first find a synchronization beacon, which consumes extra energy.

More sophisticated probabilistic collision avoidance method is so-called Carrier Sense Multiple Access (CSMA). With the CSMA, each node senses the channel to see if another transmission is ongoing prior to its own transmission. If a node detects the channel is busy, it postpones the transmission with a certain strategy [3][4]. Depending on the strategy, there are many variations of CSMA. For example, in the standard of wireless LAN protocol IEEE 802.11, each node keeps sensing the channel to detect the end of the current channel occupancy. On the other hand, in IEEE 802.15.4, a node does not keep listening once it detects the channel is busy. Instead, it backs off for a random number of slots, and senses the channel again. The main reason of the variation is power consumption. Since most wireless devices are mobile devices, they are very sensitive to the power consumption problem. CSMA can utilize the slotted channel by synchronizing the beginning of each transmission as in slotted ALOHA [3]. Many parameters affect the throughput of CSMA, and thus it is hard to mention about the effective channel utilization in a lump. It is, however, clear that most of the CSMA show much better performance than the (slotted) ALOHA [3]. The defect of CSMA is that it consumes much more power than the (slotted) ALOHA to sense the channel. The key difference between IEEE 802.11 and IEEE 802.15.4 is also related to this power consumption. The main idea of IEEE 802.15.4 is to reduce the power consumption by not continuing to sense the channel even when the channel is busy.

From these perspectives, IEEE 802.15.4 could be considered for our objective-indoor mobile tracking based on active RFID. Nevertheless, it is not efficient to adapt IEEE 802.15.4 in the pristine form since the key design assumption is completely different from that of the RFID system. IEEE 802.15.4 has been designed for data communication between nodes, and thus the packet length needs to be variable. On the other hand, RFID system is for the identification of a tag, hence fixed and short packet length suffices. These features prevent us from exploiting the advantages of CSMA because it requires a process of detecting the channel status called a clear channel assessment, or CCA. To perform CCA successfully, a tag has to

listen to the channel for a certain amount of time that varies depending on the physical channel encoding. That is, a packet frame shorter than the threshold time cannot be detected by the CCA yielding the CSMA useless [4]. Therefore, the CCA mechanism may not be useful for an RFID system with a short and fixed length packet. We have presented a simulation result of performance comparison between slotted CSMA and slotted ALOHA varying the ratio of two slot counts (Fig. 1). For the same duration, each method can have different slot count depending on the minimum CCA duration and packet length. For example, with the fixed length ID packet of 10 symbols, a slot length for the slotted ALOHA would be set to the same 10 symbols. On the other hand, the slotted CSMA would set the slot length to the minimum CCA duration regardless of the packet length. Therefore, if the minimum CCA duration is five symbols, the slotted CSMA would have two times more slots than the slotted ALOHA for the same duration. During the simulation (Fig. 1), the slot count of slotted ALOHA was fixed to 1000 while that of the slotted CSMA was varied from 1000 to 4000 and thus varying the slot count ratio from 1.0 to 4.0. The simulation was repeated three times for 700, 1000, and 1300 tags, respectively. As it can be easily inferred, the throughput of the slotted CSMA will increase as the slot count increases, hence the CCA duration will get shorter. Slotted ALOHA shows better performance until the slot count ratio reaches 2.0 (Fig. 1). Moreover, the throughput is only 10% higher even when the ratio is 4.0. Considering that the power consumption is a critical key for the battery powered mobile entities, the small amount of the performance degradation is negligible in return for the power saving. Consequently, slotted ALOHA is better suited than the slotted CSMA for short and fixed packet length as in RFID system.

2.2 Deterministic Methods

As mentioned previously, RFID is not for data communication, but for a process of tag identification. Unlike other communication systems, RFID system does not have to assume random transmissions. In other words, a transmission scheduling is possible as long as the tags can be identified within a given period. Generally, however, specific list of the available tags cannot be known at any moment, and thus a completely deterministic scheduling is impossible. Nevertheless, there is still a chance to schedule the tag transmissions under certain conditions. If a reader (or a receiver) can detect a collision in a bit unit, it can schedule the tags to avoid collisions in next interrogation by suppressing half of the collided tags. Since there are only two cases, zero or one for a bit, it can recognize a tag in constant time by interrogating the tags for each bit of zero and one, respectively. For example, if the first bit of a transmitted tag ID collides, it is clear that there are both tags with the first bit of zero and one. Therefore, the interrogator can suppress either of the tags with the first bit zero or one to avoid collision in the next interrogation. Finally, the reader can recognize a full tag ID by repeating this process for each tag bit [5][7]. This kind of scheme is called a deterministic collision avoidance method. As the name implies, this method can acquire a tag ID in constant time, but it requires a large number of interrogations for single tag identification. For example, the required number of interrogations for a specific tag with the *basic binary search algorithm* [4] is:

$$I_{BBS} = \frac{\log n}{\log 2} \quad (1)$$

where n is the number of available tags.

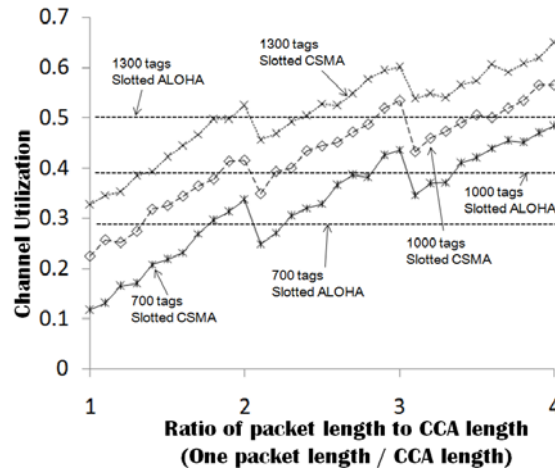


Fig. 1. Simulated channel utilization for slotted ALOHA and slotted CSMA varying the ratio of packet length to CCA length. The simulation was repeated three times for 700, 1000, and 1300 tags, respectively. The slot count for the slotted ALOHA was fixed to 1000 for all cases

Likewise, the required interrogation count with n available tags regarding *bit-by-bit binary search tree algorithm* [8][9] proposed by Auto-ID center is:

$$I_{BBS} = n \times j \quad (2)$$

where j is length of the ID bits. As shown in (1) and (2), the required number of interrogations is directly proportional to the number of available tags. The problem is that all tags should keep listening all the time. For the passive type RFID, the power is supplied by the magnetic field of interrogation, it is free from the energy efficiency issue. Active type RFID, however, should consider the energy efficiency seriously since tags are activated by their own batteries. Consequently, pure deterministic algorithms that do not consider the energy efficiency are not applicable for the active type RFID.

3. System Analysis

3.1 System Configuration

The system for which we are developing the collision avoidance algorithm is a domain specific indoor tracking system based on active RFID. In this system, the entire domain is divided into several areas. Then control units, called base station (BS), are installed at specific locations for each divided area. The BS is used to control transmission congestion within the area, hence playing a key role in our algorithm. Apart from the BS, readers are installed more densely considering the transmission coverage of a tag. Finally, it is assumed that tags be scattered around the entire domain. They are attached to either a person or an asset having a free will to move around anywhere. That is, a tag could appear or disappear in the control area of a BS anytime.

3.2 Design Considerations

Several characteristics of the aforementioned system should be considered in designing the algorithm. First, the most important feature is that the tags tend to be motionless for most of

the time rather than continuously moving around. For example, an employee, the carrier of a tag, would spend most of his or her working hours in a certain area. It is true even when the tag is attached to an asset such as a laptop. This static characteristic of a tag provides us with a chance of scheduling, hence improving the performance rather than entirely relying on a probabilistic approach. Second, the interval between two successful transmissions should be considered as a key factor in designing the system. Considering that the main purpose of the system is the management of the resources, the identification period is one of the key parameters in terms of consistency. In addition, absence of the tag is usually judged by the elapsed time from last reception, and thus the maximum interval should be bounded by a certain range. Finally, energy efficiency is a key design consideration as well. The tags for active type RFID are supplied with the power by their own batteries. Since most of the indoor tracking applications do not allow a frequent charging or replacement of batteries, the lifetime of the battery is a key factor for the successful introduction of the system. Therefore, the algorithm should consider an aspect of efficient power consumption as well as the throughput.

4. Proposed Algorithm

4.1 Behavioral Description

As mentioned previously, tags have both of the static and dynamic aspects. The static characteristic that a tag tends to stay in a specific area motivates scheduling of the tags. On the other hand, the dynamic characteristic that a tag can join or leave the control area freely should also be taken under consideration. To reflect the probabilistic behavior, the idea of slotted ALOHA has been borrowed in our algorithm. That is, a certain amount of time is allocated for the newly joined tags for random transmission. We call the period *Random Tag Access Period*, or RTAP. If a tag succeeds the transmission during RTAP, BS turns the tag into a scheduled mode by describing the required information in the ACK packet. Then the tag is provided with an exclusive slot so that a successful transmission is guaranteed from the next turn. We call the set of these exclusively allocated slots a *Scheduled Tag Access Period*, or STAP. The remaining work is to combine the STAP with RTAP. As mentioned previously, the identification interval is one of the important system parameters. For this, we define a term 'ROUND' as a required interval between two successful transmissions and let this include a STAP for a guaranteed successful transmission. The rest of the ROUND is filled with RTAP(s).

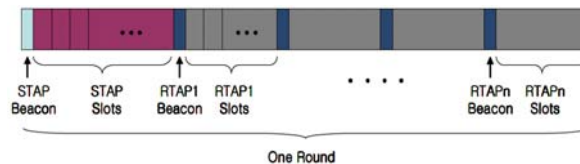


Fig. 2. One round composed of one STAP and multiple RTAPs

Fig. 2 depicts the configuration of a ROUND. At the beginning of every STAP and RTAP, beacon signals are placed to synchronize the transmissions with the slot instances. First, a newly joined tag in the control area starts in random mode and tries to search a RTAP beacon by waking up periodically. Every RTAP beacon includes an ID of the base station as well as the number of slots in the following RTAP. Once a tag finds the RTAP beacon, it transmits its ID at a randomly chosen slot during the following RTAP. If no other tag has transmitted during the slot, which indicates successful transmission, then the BS replies to the tag with an

ACK packet that contains the required information to turn the tag into scheduled mode. For example, it would contain the allocated slot index in STAP, and the duration until the next STAP beacon so the tag can fall into sleep mode, hence saving the energy. On the other hand, if more than two tags transmit at a same slot causing a collision, the BS would skip the ACK for the slot. Then the tags that fail to receive the ACK would fall into a sleep mode until next RTAP starts. For the second try, the effort of finding the RTAP beacon could be omitted or minimized since the previous RTAP beacon may contain the duration until the next RTAP. Then, the tag that woke up at the next round would choose the slot randomly and transmit the ID packet again. Since each tag would choose the slot randomly for every RTAP, no synchronized continuous failure would not be forced. That is, a collision incurred by two tag transmissions at a same slot may not be repeated during the next RTAP since those tags would choose the next transmission slot randomly, and hence different slots.

From the discussion above, it is obvious that the ROUND length should be longer than maximum STAP length. Since the maximum STAP length is automatically determined by the available tag count, the length of ROUND is merely dependent of the required RTAP length. Meanwhile, the average period of tag identification is directly proportional to the ROUND length. Normally, the maximum period is bounded by the characteristic of the application. For instance, a tag attached to a person may need to be identified every few seconds considering the walking speed of the person. Actually, the faster the identification period is, the better it is for almost every application. Practically, however, the minimum period is also bounded by the required life cycle of the tag battery, which is directly proportional to the ROUND length. Consequently, it is more reasonable to decide the ROUND length first, considering the requirements of the application as well as the life cycle of the battery. Then, the RTAP length is automatically determined to be the rest of the ROUND length excluding the STAP length.

4.2 STAP Management

Once a tag is scheduled, an exclusive slot is allocated in STAP and assigned for the tag. Therefore, the transmission always succeeds as long as the tag stays in the control area of the BS. On the other hand, if a scheduled tag leaves the area, hence failing to transmit at the expected slot in STAP, the tag will turn itself into random mode starting to seek an RTAP beacon in the new area. Meanwhile, the BS will also notice the absence of the tag by failing to receive the tag transmission at the expected slot in STAP. Then it marks the slot as ‘empty’ for further use rather than shrinking the STAP immediately. If a slot in the middle of STAP is removed, all other slots after the removed one should be shifted forward incurring a cost of informing the corresponding tags. To avoid this redundancy, the slot is removed only when the failure occurs at the end of the STAP (Fig. 3).

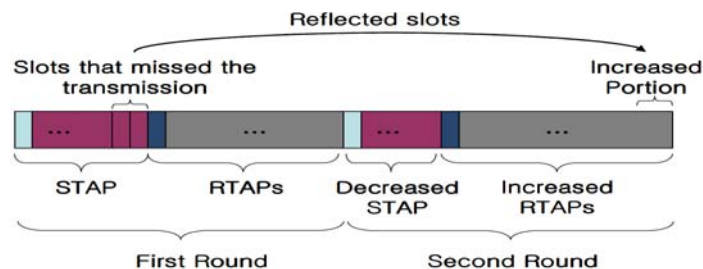


Fig. 3. Slot adjustment at the end of the STAP

4.3 Decision on Optimal RTAP Count

Starting the slot count of the STAP at zero, it is adjusted dynamically as the tags join or leave the scope. The rest of the ROUND is allocated for RTAP(s). If the range is dedicated to a single RTAP, resulting in only one beacon signal, the listening time to find the beacon could be lengthy, incurring waste of power consumption. On the other hand, if the range is divided into an excessively large number of RTAPs, it may decrease the rate of successful transmission due to the relatively small number of slots than that of the ready-to-transmit tags. Therefore, it is important to decide a proper slot count of RTAP. Once the slot count in a RTAP is determined, the number of RTAPs in a ROUND can be automatically determined since the length of ROUND is a fixed value.

Assuming that n unscheduled tags are ready-to-transmit by hearing the RTAP beacon signal, the probability that a tag successfully transmits at a specific slot can be calculated as follows:

$$P_{slot}(n, L) = \frac{1}{L} \cdot \left(1 - \frac{1}{L}\right)^{n-1} \quad (3)$$

where L is the number of slots in the RTAP. Since there are L slots in the RTAP, the probability of successful transmission through the RTAP period is:

$$P_{succ}(n, L) = \left(1 - \frac{1}{L}\right)^{n-1} \quad (4)$$

If we assume that during the RTAP a tag is allowed to transmit only once, the average trial count until the transmission succeeds is:

$$C_{trial}(n, L) = \frac{1}{P_{succ}} = \frac{1}{\left(1 - \frac{1}{L}\right)^{n-1}} \quad (5)$$

Now, we define a cost function J as follows:

$$\begin{aligned} J(n, L) &= \text{Listening Power} + \text{Transmission Power} + \text{Trial Duration} \\ &= \alpha C_{trial} \left(\frac{sL}{2} + b\right) + \beta C_{trial} s + \gamma C_{trial} sL \end{aligned} \quad (6)$$

where s is the slot length, b is the length of beacon signal, α , β , and γ are coefficients for listening power, transmission power, and the trial duration before the successful transmission, respectively. Equation (6) illustrates the overall cost regarding the power consumption and duration for a successful transmission. Thus, L should be determined in such a way that minimizes the cost function J . Rewriting (6) yields:

$$\begin{aligned} J(n, L) &= L C_{trial} s \left(\frac{\alpha}{2} + \gamma\right) + C_{trial} (\alpha b + \beta s) \\ &= \frac{L}{\left(1 - \frac{1}{L}\right)^{n-1}} s \left(\frac{\alpha}{2} + \gamma\right) + \frac{1}{\left(1 - \frac{1}{L}\right)^{n-1}} (\alpha b + \beta s) \\ &= J_1(n, L) + J_2(n, L) \end{aligned} \quad (7)$$

Since differentiating J_1 with respect to L is a complicated process, differentiating J_1 taking a monotonically increasing function \log yields:

$$\frac{d \log J_1}{dL} = \frac{L - n}{L(L - 1)} = 0 \quad (8)$$

and

$$\frac{d^2 \log J_1}{dL^2} = \frac{-L^2 + 2nL - n}{(L^2 - L)^2} > 0 \text{ for } n \geq 2 \quad (9)$$

From (8) and (9), it is obvious that J_1 has a minimum at $L = n$. On the other hand, J_2 is a monotonically decreasing function, and thus has no minimum. The coefficient β indicates a relative importance of the power consumption for transmission, and hence is much smaller than the other coefficients. In addition, n , the number of tags, is generally more than dozens or hundreds yielding the big optimal L for J_1 . Therefore, the impact of J_2 can be ignored. To sum up, an optimal slot count L for the entire cost function J can be determined in the same way as the optimal L for J_1 :

$$L_{opt} = n \quad (10)$$

Meanwhile, the probability that a specific slot remains empty can be obtained as:

$$P_{empty}(n, L) = \left(1 - \frac{1}{L}\right)^n \quad (11)$$

Then, the expected count of the empty slots is:

$$E_{empty}(n, L) = L \cdot P_{empty} = L \cdot \left(1 - \frac{1}{L}\right)^n \quad (12)$$

Since we can measure the empty slot count E_{empty} from the result of previous RTAP, the number of transmitted tags can be estimated as:

$$n = \frac{\log\left(\frac{E_{empty}}{L}\right)}{\log\left(1 - \frac{1}{L}\right)} \quad (13)$$

After an RTAP with a certain slot count L , the number of transmitted tags during the RTAP can be obtained probabilistically as in (13). Then from (10), the optimal slot counter for the next RTAP can be determined as:

$$L_{opt} = \frac{\log\left(\frac{E_{empty}}{L}\right)}{\log\left(1 - \frac{1}{L}\right)} - N_{succ} \quad (14)$$

where N_{succ} is the number of successfully transmitted tags during the last RTAP.

Meanwhile, the increment of RTAP slot count increases the effort of finding the beacon signal as well, hence incurring increased power consumption. For this reason, small and fixed number of RTAP slots is preferred in terms of energy efficiency. Hence, we make the RTAP beacon include a transmission probability P_{trans} with which a tag decides whether to transmit or not. Since the optimal slot count can be acquired by analyzing previous RTAP, the same

throughput can be achieved by adjusting P_{trans} with any L . Then the number of available ready-to-transmit tags can be calculated as:

$$N_{est} = \frac{\log\left(\frac{E_{empty}}{L}\right)}{\log\left(1 - \frac{1}{L}\right)P_{trans-prev}} - N_{succ} \quad (15)$$

where $P_{trans-prev}$ is the transmission probability used in the previous RTAP. Then the optimal transmission probability for the next RTAP can be obtained as follows:

$$P_{trans} = \frac{L}{N_{est}} \quad (16)$$

where L is a fixed slot count in a single RTAP. Since the optimal throughput can be obtained regardless of L , we can determine the slot count merely in terms of energy efficiency.

5. Simulations

5.1 Steady-State Stability of STAP

As described in section 4.2, the slot count of STAP is not immediately re-adjusted upon the disappearance of a scheduled tag. The slot is simply marked as empty and reused for a newly joined tag. The slot is removed only when the scheduled tag at the last slot in STAP disappears. Therefore, it is important that the number of STAP slot be maintained at a certain level without diverging.

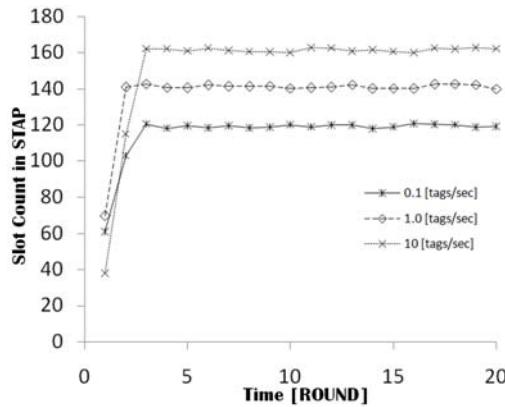


Fig. 4. Slot count in STAP with variations of tag flow rate

Fig. 4 shows the simulation result of the steady-state stability regarding the STAP slot count. We first assumed that there are 100 tags already in the control area. Then the tag arrivals and departures were randomly generated at the rate of 0.1, 1 and 10 [tags/sec]. As the ROUND repeats, the slot count in the STAP keeps increasing. Once it is saturated, it changes no more. Consequently, the steady-state-stability of the system regarding the STAP slot count is guaranteed as long as the average arrival rate is equal to or less than the departure rate.

5.2 Channel Utilization

To assess the validity of the optimal slot count in terms of channel utilization, we performed a simulation with variations of available tag counts. Since our algorithm employs two different periods, STAP and RTAP, the channel utilization should be considered for each period, respectively.

During the STAP, all slots are exclusively allocated guaranteeing perfect transmission. Thus, it is meaningless to consider the channel utilization of STAP alone. Instead, we performed some analysis and simulations to prove the efficiency of our algorithm by comparing with the hybrid super frame of IEEE 802.15.4 MAC. The superframe can have an active and an inactive portion. The active portion consists of 16 equally divided time slots that are further separated into contention access period (CAP) and contention free period (CFP). Any device wishing to communicate during the CAP shall compete with other devices using a slotted CSMA-CA mechanism as in the RTAP of our proposed method. On the other hand, the CFP also contains up to seven guaranteed time slots (GTSs). The IEEE 802.15.4 fixes the duration of the superframe to 960 symbols (one symbol corresponds to 4 bits, assuming 2.4 GHz frequency band and 250Kbps of bit rate). Thus, each slot can accommodate 30 bytes, and the minimum duration of the GTS slot becomes 30 bytes as well. If we employ the IEEE 802.15.4 MAC for our application, the best throughput can be obtained when the entire superframe is dedicated to CFP with the maximum number of GTS, seven. Since each GTS is exclusively allocated to a single tag and so is the CFP beacon, the superframe would consist of eight time slots allowing seven tags to transmit their IDs during the period. Thus, the best channel utilization of the IEEE 802.15.4 MAC for the tag identification can be obtained as follows:

$$\text{Channel Utilization}_{CFP} = \frac{7I}{30 \times 8} \quad (17)$$

where I is the length of the ID packet transmitted from a tag. On the contrary, each slot in our proposed method exactly fits the required packet length yielding no waste for an ID transmission. Since the STAP requires a fixed size beacon only once during the entire tag transmission, the channel utilization can be calculated as:

$$\text{Channel Utilization}_{STAP} = 1 - \frac{B}{nI} \quad (18)$$

where B is length of the beacon and n is the number of scheduled tags. Considering that the ID length is just a few bytes in most cases, I would be much less than 30, yielding a low channel utilization of CFP. Contrarily, the number of available tags could be more than hundreds or thousands yielding comparably higher channel utilization from (18). **Fig. 5** depicts the estimated channel utilizations for both of the algorithms with variations of I . As expected, our method shows much higher throughput. The length of a time slot in the superframe is a constant value, which is much longer than the ID packet. Thus, short and fixed size packets as used in our application cause waste of bytes in a time slot, yielding low throughput. In addition, the strict limitation in the number of GTSs also incurs the decrease of throughput with excessive number of beacons.

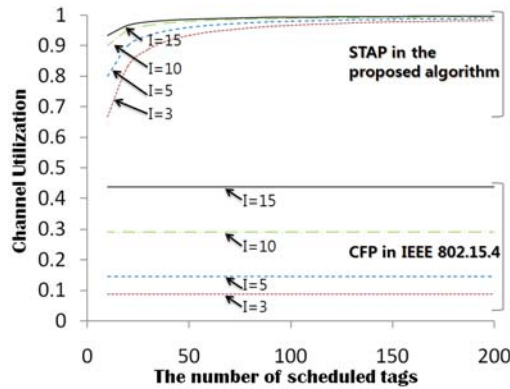


Fig. 5. Channel utilizations for CFP in IEEE 802.15.4 MAC and STAP in the proposed method with the variation of I , length of the ID packet

Meanwhile, **Fig. 6** depicts the simulation results regarding the channel utilization of RTAP. As derived in section 4.3, the best throughput is obtained when the slot count in RTAP is the same as the available tag count. It is also noted that the maximum throughput converges to a constant value regardless of the available tag count. Since the optimal slot count of RTAP is the same as the available tag count, the maximum channel utilization can be calculated from (4) by replacing n with L . The calculated optimal channel utilization is illustrated in **Fig. 7** with the simulation result. As in the result of **Fig. 6**, the maximum channel utilization in **Fig. 7** also converges to 0.37.

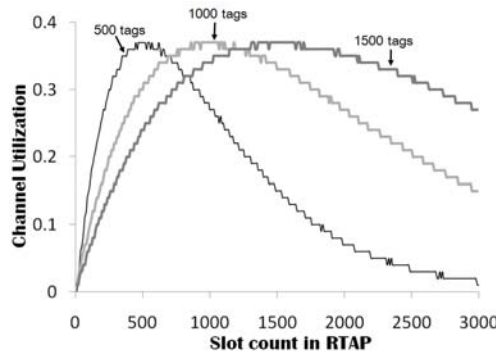


Fig. 6. Channel utilization for various slot counts of RTAP

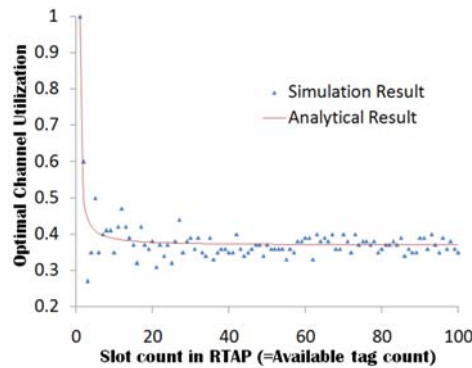


Fig. 7. Optimal channel utilization for various tag counts

5.3 System Performance

Once a tag is scheduled, it does not affect the performance of the system anymore. Thus, we merely focus on the performance of the RTAP. There are two key performance parameters for the RTAP. One is the scheduling time for a newly joined tag and the other is the power that a tag consumes until it is scheduled. This includes an average listening time for a beacon searching as well as the number of required RTAP count for a successful transmission. Although the system can be constructed based on any kind of physical layer, we assumed the standard IEEE 802.15.4 for being pragmatic. The data rate was set to 250 Kbps and 8 bytes of the physical layer data were appended to each packet (6 bytes preamble and 2 bytes FCS). Data size for RTAP beacon, STAP beacon, Tag identification packet and the ACK were set to 7, 4, 2, and 8 bytes, respectively. Finally, the number of RTAP slots is fixed to 30 and the simulation was performed varying the number of unscheduled tags from 100 to 2000 by step size of 100. Since the transmission probability is calculated based on the optimal slot count analysis derived in section 4.3, the fixed count of RTAP slots does not affect the throughput. For example, if the slot count were doubled, the transmission probability would be doubled as well, hence maintaining the optimal slot count.

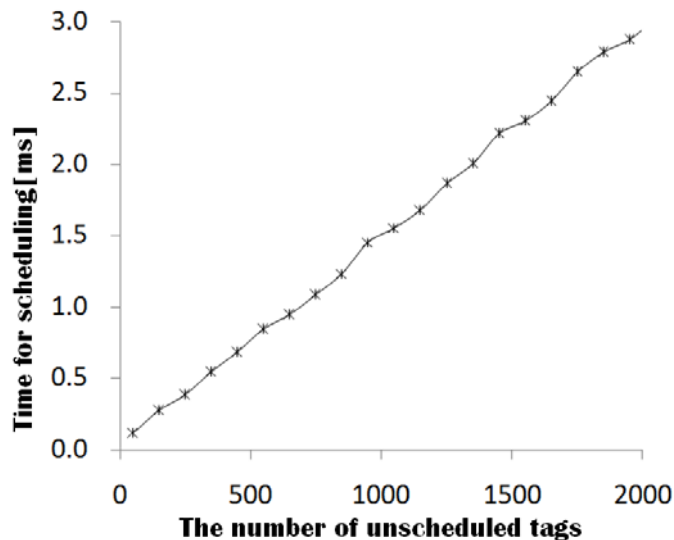


Fig. 8. Average scheduling time for a tag

Fig. 8 depicts the average scheduling time for a tag. As the graph shows, the increment of the scheduling time is linearly proportional to the increment of the unscheduled tag count. It proves that the system maintains a constant throughput, which is optimal regardless of the tag count, by running the optimal slot count mechanism. Moreover, there are few cases of such massive emerging of unscheduled tags except for the starting time of the system. Thus, the result seems quite acceptable in practical manner.

Likewise, simulations for the listening and transmission times of a tag until it be scheduled were performed. Since, most of the power consumption happens during listening and transmission phase, the accumulated time for those duration is a key performance parameter in terms of the power consumption. **Fig. 9** and **Fig. 10** show the average listening and transmission times of a tag, respectively, with variations of unscheduled tag counts.

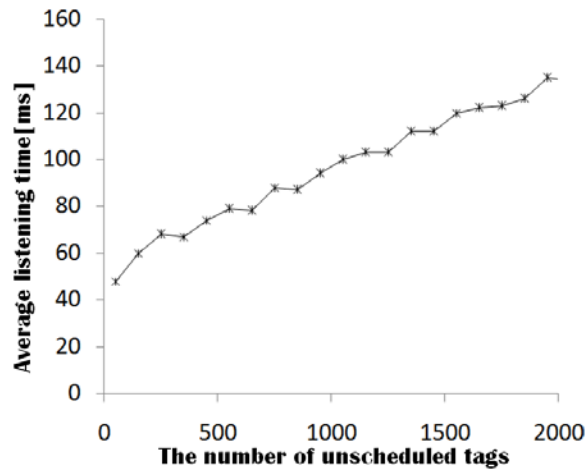


Fig. 9. Average listening time for an unscheduled tag

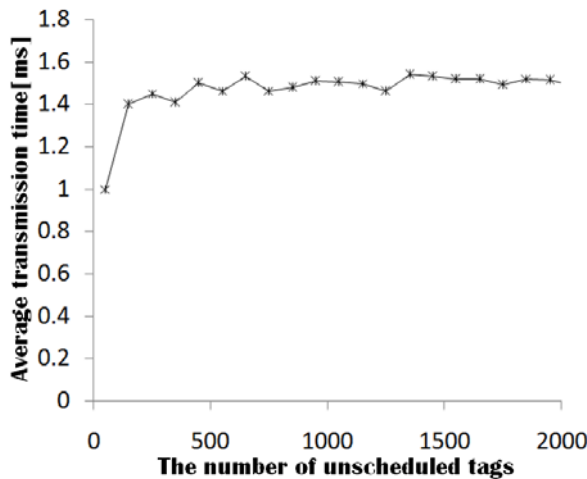


Fig. 10. Average transmission time for an unscheduled tag

As shown in **Fig. 9**, the listening time linearly increases with the increment of the unscheduled tag count. The transmission time, however, is almost a constant value regardless of the unscheduled tag count. It also results from the scheme of the optimal slot count maintenance. As the number of unscheduled tags increases, the transmission probability is adjusted to maintain the optimal slot count. Therefore, the trial count of transmission is always maintained at minimum, and hence the constant and minimal transmission duration. On the other hand, a tag has to listen to the beacon every time it wakes up for the transmission decision. As the number of unscheduled tags increases, the transmission probability is decreased suppressing the transmissions. Thus, a tag requires more RTAPs for being scheduled. Nevertheless, thanks to the optimal throughput mechanism, the increment of listening time can be kept linear regardless of the absolute number of unscheduled tag count. If no scheduling were performed, the probability of successful transmission would dramatically decrease, causing an exponential increment of listening time. For example, under the normal slotted ALOHA, the throughput soon hits the top and starts to fall down as the number of tags increases.

6. Conclusion

Most of the existing collision avoidance methods are designed for passive type RFID or data communication system. The methods for passive type RFID do not consider the power consumption at all since the tags are activated by the interrogation itself. On the other hand, a data communication system assumes a variable and comparably longer packet length. Contrarily, an RFID system is concerned with the identification of tags rather than data transferring, hence uses short and fixed length packets. Moreover, tags for an indoor tracking system have both of the static and dynamic features. In this paper, we have proposed a dedicated collision avoidance algorithm for indoor tracking system using active type RFID. A preliminary analysis of the existing methods has been performed regarding the proposed system. Then we have proposed an effective collision avoidance scheme for indoor tracking system by exploiting the unique characteristics of the system. In addition, the required parameters have been determined through mathematical analysis for the best throughput. Several simulations have conducted that illustrate the efficiency of the proposed system. Since most of the indoor tracking systems employ dedicated hardware, the collision avoidance scheme is highly likely to be self-implemented. Especially, the quantitative analysis of the throughput is essential for the efficient system operation. As a result, our proposed scheme seems to be extremely useful for those who develop indoor tracking systems.

References

- [1] H. S. Choi, J. R. Cha and J. H. Kim, "Fast Wireless Anti-collision Algorithm in Ubiquitous ID System," in *Proc. of IEEE VTC 2004*, L.A., USA, Sep. 26-29, 2004
- [2] T. R. Park, T.H. Kim, J.Y. Choi and W.H. Kwon, "Throughput and energy consumption analysis of IEEE 802.15.4 slotted CSMA/CA," *ELECTRONIC LETTERS*, vol. 41, no. 18, Sept. 2005
- [3] C. Floerkemeier, "Transmission control scheme for fast RFID object identification," *IEEE PerCom Workshop on Pervasive Wireless Networking*, Mar. 2006
- [4] A. Micic, A. Nayak, D. Simplot-Ryl and I. Stojmenovic, "A 332 hybrid randomized protocol for RFID tag identification," *IEEE International Workshop on Next Generation Wireless Networks*, Goa, India, 2005
- [5] H. Vogt, "Efficient Object Identification with Passive RFID tags," in *Proc. of International Conf. on Pervasive Computing, Zurich*, 2002, pp. 98-113
- [6] S. Chen and V. Thomas, "Optimization of inductive RFID technology", *IEEE International Symposium on Electronics and Environment*, 2001
- [7] J. R. Cha and J. H. Kim, "Novel Anti-collision Algorithms for Fast Object Identification in RFID System", in *Proc. of International Conf. on Parallel and Distributed Systems*, 2005
- [8] T. W. Hwang, B. G. Lee, Y. S. Kim, D. Y. Suh and J. S. Kim, "Improved Anti-collision Scheme for High Speed Identification in RFID System", in *Proc. of ICICIC*, Beijing, China, Aug. 30-Sep. 01, 2006
- [9] Zhou, F., Jing, D., Huang, C., and Min H. "Optimizing the Power Consumption of Passive Electronic Tags for Anticollision Schemes" in *Proc. of the 5th ASICON*, Beijing, China, Oct. 2003, 1213-1217
- [10] I. Cidon and M. Sidi, "Conflict multiplicity estimation and batch resolution algorithms", *IEEE Transactions on Information Theory*, vol. 34, no. 1, Jan. 1988
- [11] J. H. Myung and W. J. Lee, "Adaptive Splitting Protocols for RFID Tag Collision Arbitration" in *Proc. of MobiHoc*, Florence, Italy, May 22-25, 2006
- [12] F. C. Schoute, "Dynamic framed length ALOHA", *IEEE Transactions on Communications*, vol. 31, no. 4, Apr 1983
- [13] K. Finkenzerler, "RFID Handbook: Fundamentals and Applications in Contactless Smart Cards and Identification 2nd ed.," *John Wiley & Sons*, Mar. 2003

- [14] L. M. NI and Y. LIU, Y. C. LAU and A. P. PATIL, "LANDMARC: Indoor Location Sensing Using Active RFID", *Wireless Networks*, vol. 10, 2004
- [15] M. A. Bonuccelli, F. Lonetti and F. Martelli, "Tree Slotted Aloha: a New Protocol for Tag Identification in RFID Networks", in *Proc. of IEEE WoWMom*, Niagara-Falls, Buffalo-NY, June 26-29, 2006
- [16] M. Jaoccurt, A. Ehram, U. Gehrig, "Contactless Identification Device With Anticollision Algorithm," *IEEE Computer Society CSCC'99, Conf. on Circuits, Systems, Computers and Communications*, Jul. 4-8 Athens, 1999
- [17] M. Kodialam, T. Nandagopal, "Fast and Reliable Estimation Schemes in RFID Systems", in *Proc. of MobiCom*, L.A., USA, Sep. 23-26, 2006
- [18] P. Bahl and V.N. Padmanabhan, "RADAR: An in-building RF-based user location and tracking system", in *Proc. of IEEE INFOCOM 2000*, Tel-Aviv, Israel, Mar. 2000
- [19] D. Engels and S. Sarma, "The reader collision problem", *IEEE Systems, Man and Cybernetics*, 2002
- [20] S. Lee, S. Joo and C. Lee, "An enhanced dynamic framed slotted ALOHA algorithm for RFID tag identification", *IEEE MobiQuitous*, 2005
- [21] S. Sarma, J. Waldrop, and D. Engels, "Colorwave: An Anticollision Algorithm for the Reader Collision Problem," *IEEE International Conf. on Communications, ICC '03*, vol. 2, May, 2003, pp. 206-1210
- [22] As N. Li, X. Duan, Y. Wu, S. Hua and B. Jiao, "An Anti-Collision Algorithm For Active RFID," in *Proc of, WiCom 2006*, Wuhan, China, Sep. 22-24, 2006
- [23] Auto-ID Center, *Draft Protocol Specification for a Class 0 Radio Frequency Identification tag*, 2003
- [24] C. S. Kim, K. L. Park, H. C. Kim and S. D. Kim, "An Efficient Stochastic Anti-collision Algorithm using Bit-Slot Mechanism", *PDPTA04*, 2004



Sekyung Han received his B.S. degree in electrical engineering and computer science from Hanyang University, Seoul, Korea in 2002, his M.S. in School of electrical engineering and computer science from Seoul National University (SNU), Seoul, Korea, in 2007. He has accumulated vast experience in the IT industry and joined the Institute of SK Energy as a research engineer in 2007. He was involved in the development of the battery system for hybrid electric vehicles. Specifically, he was engaged in the development of the battery management system and the Battery-Hardware In the Loop Simulations (B-HILS). Currently, he is doing his Ph.D in Information Science and Technology from the University of Tokyo, Japan. His main research interest is integration of the IT technologies with Smart Grid. Especially, Vehicle-to-Grid is his primary interest at the moment.



Yeonsuk Choi received his B.S degree in mechanical engineering from Sungkyunkwan University, Soowon, Korea in 1990. He received the M.S. degree in Mechanical Engineering from Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea in 1992. From 1992 to 1995, he was a research engineer in Daewoo Electronics. He also ran his own IT company, Changwah-tech, from 1995 to 2005. From 2005 to 2007, he was an assistant professor at the Industry-Academy Cooperation Found Center, Hoseo University, Chunan, Korea. Since 2007, he has been with the Faculty of Liberal Arts at the same university. His main interests are ubiquitous city, indoor wireless position estimation, and long wavelength wireless communication.



Masayuki Iwai received his Ph.D. (Media and Governance, Keio University) in 2004. He was the lecturer at Keio University, Graduate School of Media and Governance until 2008. From 2008, he joined JST/CREST project at the University of Tokyo, Department of Informatics and Electronics, Institute of Industrial Science. From 2009, he has been an Assistant Professor at the University of Tokyo, Department of Informatics and Electronics, Institute of Industrial Science as a Research Assistant Professor. His interesting research fields are Sensor Database, Tiny Sensor Node, RFID Antenna, Distributed Computing, Ubiquitous Application, Human Probe, Pedestrian Detection, Media Art. He has been managing KAKEN Grants-in-Aid for Scientific Researches in Japan.



Kaoru Sezaki received his B.E., M.E. and Dr.E. degrees in electrical engineering from the University of Tokyo in 1984, 1986, and 1989, respectively. He joined the Institute of Industrial Science at the University of Tokyo in 1989. He is now an associate professor at the Center for Spatial Information Science at the University of Tokyo. From 1994 to 2000, he was a guest associate professor at the National Center for Science Information Systems. He has been a guest associate professor at National Institute for Informatics since 2000. He has been a special member of Telecommunications Business Dispute Settlement Commission since 2001. From 1996 to 1997, he was a visiting scholar at the Univ. of California, San Diego. His research interests include communication networks, location- and context-aware network services, high-speed switching systems, Collaboration systems with haptics, GIS and image processing. He is a member of the IEEE.