PAPER *Special Section on Ubiquitous Networks*

Framed ALOHA for Multiple RFID Objects Identification

Bin ZHEN[†a)], **Mamoru KOBAYASHI**[†b)], ***Nonmembers*, *and*** **Masashi SHIMIZU**[†c)], ***Member***

SUMMARY Radio frequency identification (RFID) enables everyday objects to be identified, tracked, and recorded. The RFID tags are must be extremely simple and of low cost to be suitable for large scale application. An efficient RFID anti-collision mechanism must have low access latency and low power consumption. This paper investigates how to recognize multiple RFID tags within the reader's interrogation ranges without knowing the number of tags in advance by using framed ALOHA. To optimize power consumption and overall tag read time, a combinatory model was proposed to analyze both passive and active tags with consideration on capture effect over wireless fading channels. By using the model, the parameters on tag set estimation and frame size update were presented. Simulations were conducted to verify the analysis. In addition, we come up with a proposal to combat capture effect in deterministic anti-collision algorithms.

key words: *RFID, anti-collision, framed ALOHA, low energy*

1. Introduction

The radio frequency identification (RFID) system consists of a reader and a large numbers of small, low-cost tags with unique IDs [1]. The RFID tags can be embedded in everyday objects to track location, monitor security and event status, record environmental conditions, and even control objects from a distance without being in line-of-sight (LOS). The enabled object-object communication bridges the gap between the physical world and the virtual network world about "when," "what," "where" and "result" [2].

The RFID tags can be either active or passive [1]. Active tags are continually powered by internal batteries, while passive tags have no internal power and reflect energy from the reader for communication. Consequently, active tags can be read from a greater distance than passive tags. Moreover, active tags have more functions than passive tags, e.g. data storage and sensor capabilities.

The RFID tags have restricted cost, size and lifetime requirements. Significant market penetration can be expected only if the passive tags are priced about 5 cents [3]. For the active tags, the highest price should be below a US$. The tags have to be very simple in order to be as cheap as possible. The lifetime of active tags is over when the battery is exhausted. It is uneconomical to replace or recharge the active tag battery because of large number of small and cheap nodes. Therefore, the RFID tags have to work in a resource-scarce environment, where power consumption, computational capacity, memory storage and even gate counts are highly limited [4]. Furthermore, limited available bandwidth means that all tags must share a common broadcast channel. This leads to mutual interference when there is more than one tag within interrogation zone of a reader, which is known as packet *collision*. A natural question is: what is the best communication protocol so that the tags can be read as fast and reliable as possible? This is known as *anti-collision* problem. The issue becomes more challenging on considering that the tags must be simple, cheap and small enough.

The anti-collision algorithm of RFID can be either deterministic or statistic [1]. In the binary tree-walking scheme, a reader queries all nearby tags for the next bit of their ID number [5]. On detecting packet collision, the reader splits the response set and queries again until there is only one leaf tag response. The shortcoming is that the tags must have a counter to track the query bit in the tree. The clocking circuit and protocol state register are mandated at tag side. All these increase complexity of tags. In memoryless protocol, tags do not need to have time circuit and remember the protocol states [6]. It assumes some prior knowledge about the maximum number of objects to be identified and tags are uniquely identified by a binary string of k-bits. The reader explores all possible values of the k-bits string with some optimizations in the form of a hierarchical query tree. The response of tag depends only on the comparison between tag ID and the prefix string. To reduce number of tag response, M. Jacomet proposed bit-wise arbitration based algorithm for amplitude modulated passive tags [7]. A special time position source coding is used so that a bit can be correctly read even collision occurs. The deterministic solutions suffer from scalability problem since the communication complexity is on the order of ($kn^* \log_2 n$), where n is the tag number and k is the size of the ID string. The access delay might be unacceptable in the case of a large number of tags. H. Vogt used the Markov process to describe the dynamic framed ALOHA reading of passive tag [8]. Framed ALOHA is also defined in ISO/IEC active tag for item management [9]. However, the frame update mechanism is manufacturer dependent.

All of the above methods focus on optimizing access delay of tags. Battery energy is limited and scarce resource. While radio communication uses a lot of energy, reception of short range radio devices, e.g. tags, uses almost as much

Manuscript received August 2, 2004.
Manuscript revised October 10, 2004.

[†]The authors are with NTT Network Innovation Laboratories, NTT Corporation, Yokosuka-shi, 239-0487 Japan.
a) E-mail: zhen.bin@lab.ntt.co.jp
b) E-mail: kobayashi.mamoru@lab.ntt.co.jp
c) E-mail: shimizu.masashi@lab.ntt.co.jp

DOI: 10.1093/ietcom/e88–b.3.991

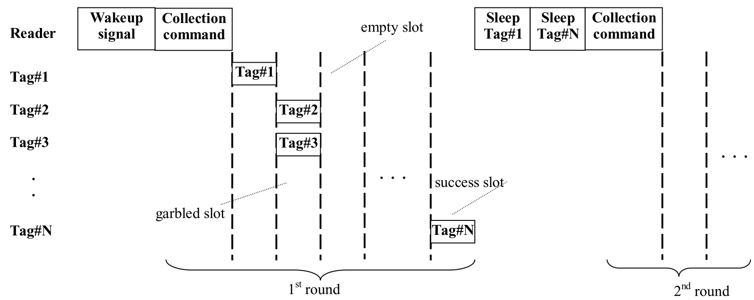


Fig. 1 IDs collection sequence of active RFID using framed ALOHA.

energy as uplink transmission. Therefore, the battery consumption can be saved by reducing both reader transmission and tag response. The RFID tags can enter sleep state where the radio reception is disabled [9]. I. Chlamtac proposed different energy-conserving strategies based on traffic load and cluster conditions of tags [4]. However, the number of tags must be known before hand. Though there are no real energy issues with passive tags, readers of passive tags are handheld devices usually. The strong data collecting signal run out the battery soon. Besides, more reader transmissions deteriorate *reader collision* issue when the reader's interrogation ranges intersect each other [10].

All above considerations make low latency and low energy requirement on multiple-access of RFID tags. This paper presents a combinatory model to analyze and optimize framed ALOHA parameters for both passive and active RFID without prior information on the number of tags in advance. The next section briefly introduces RFID and the tag ID collection procedure using framed ALOHA. Section 3 provides a mathematical combinatory model of RFID system. The simulations are given in Sect. 4 to verify the analysis. Section 5 discusses and concludes the paper.

2. Framed ALOHA Access of RFID System

RFID systems are operated at widely frequencies ranging from 135 kHz longwave to 2.4 GHz microwave range [1]. Electric, magnetic and electromagnetic wave fields are used for physical energy coupling. The *close coupling* and *remote coupling* systems are with small range, typically within 1 meter by using magnetic field as media. RFID systems with ranges significantly above 1m are known as *long range* system which operate using electromagnetic wave in the ultra-high frequency (UHF) and microwave range. The tag antennas passively *backscatter* part of irradiated power from reader back to the reader antenna with modulated data. The active tags powered with internal battery can reach more than 10 meters. Depends on the services, the basic function blocks of RFID tag comprise transmitter, receiver, sensor, multihop, encryption and battery. In this paper, we focus on the wireless tags with both transmitter and receiver operating at UHF and microwave frequency bands, which target the applications of item management.

Framed ALOHA is a variation of slotted ALOHA where a terminal is permitted to transmit once per frame which can be either fixed or variable [8], [9], [11]–[13]. Framed ALOHA imposes constraints on the retransmission probability and helps to maintain the stability of slotted ALOHA [11]–[13]. Most RFID systems work in a Reader-Talk-First mode, where the reader initiates communication and then listens for response from tags [1]. This makes framed ALOHA particularly suitable for the RFID system. A tag response is aligned at the beginning of the slot and must be finished in one slot.

The default state of active tags is Sleep state where the radio transceiver is shut down and the tag will not response to any command [1], [9]. Figure 1 shows a typical ID collection sequence starting from a Wakeup signal. Upon detection of Wakeup signal, all tags enter into Ready state awaiting commands from the reader. The followed Collection command specifies collection frame size and slot interval. Active tags randomly compute their slot numbers and response in the slot. Here, the reader may have an empty slot without any response, a garbled tag response detected from either contention transmission or invalid CRC, or a good tag response without any error. The collection round is over, after the reader sends Sleep command to all tags collected during the previous collection frame. Tags receiving the Sleep command move to Sleep state and will not participate in the subsequent collection rounds. The reader immediately starts the next read cycle by sending another Collection command with possible new frame size. This process continues until no more tag responses are detected [9]. All active tags can be read since the reader is aware of the unrecognized tags by the garbled slots. As an active tag response occurs only once in a collection round, number of tag response can be a measurement of tag power consumption[†].

In the passive RFID systems, the reader both powers and communicates with passive tags within its range [1]. During communication, the reader broadcasts a steady radio frequency power level. A typical ID collection procedure consists of only Collection command from reader to tag and random responses *vice versa*. Simple passive tags do not save any state information and only respond to a query [1], [5], [6], [8]. In addition, usually only limited frame sizes are available, e.g. 16, 32, 64 etc. [8], [14]. Tag collisions may be detected in every collection round. This distinguishes from

[†]We use both tag response and collection round in this paper.

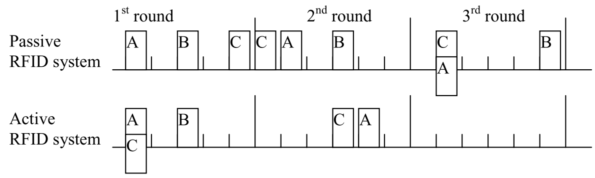


Fig. 2 Comparison of the ID collection between active tag RFID system and passive tag RFID system using framed ALOHA.

the ID collection of active RFID where there are equal or fewer numbers of tag responses in next read cycle. Therefore, statistically, we cannot expect to identify all passive tags with complete certainty. The collection procedure ends until we arrive at an assurance level. This level can be defined as a probability α, for example, $\alpha = 0.99$ denotes the probability of missing one or more passive tags is less than 1%.

Figure 2 compares the random response of active tags and passive tags in three collection rounds. Assume a frame with 5 slots and there are three tags titled A, B and C around a reader. As shown in upper panel of Fig. 2, the passive tags response in all three rounds though they have been read successfully in the first two rounds. On the contrary, the active tag B only responses in the first round. Before the 2nd round, the reader move tag B to Sleep state to save battery power. Because of collision between tag A and tag C in the 1st round, both tags response in the 2nd round. After reading all three tags in the first two rounds, there is no tag response in the 3rd round. The reader hence thinks all tags in the interrogation range have been read successfully.

3. Mathematical Model

During the ID collection procedure described above, Wakeup signal, Collection command and Sleep command are fixed and deterministic process. Thus, we only need to analyze the randomness of tag response. In the analysis, we assume tags are more or less static during ID collection. The background noise is not considered.

3.1 Static Frame Size Analysis

Given a frame size of $N(i)$ slots and $n(i)$ tags to be read in the ith collection round, the probability of q tags in a slot is binomially distributed

$$p_q(i) = \binom{n(i)}{q}\left(\frac{1}{N(i)}\right)^q\left(\frac{N(i)-1}{N(i)}\right)^{n(i)-q}, \tag{1}$$

where q=1, $p_1(i)$ is the probability of a successful ID transmission. The expected number of successful ID transmissions in a frame becomes $N(i)p_1(i)$. For passive RFID systems, the probability of missing a passive tag after R_{p_f} static frames can be given by

$$\prod_{i=1}^{R_f}\left(1 - \frac{N(i)p_1(i)}{n(i)}\right) = 1 - \alpha. \tag{2}$$

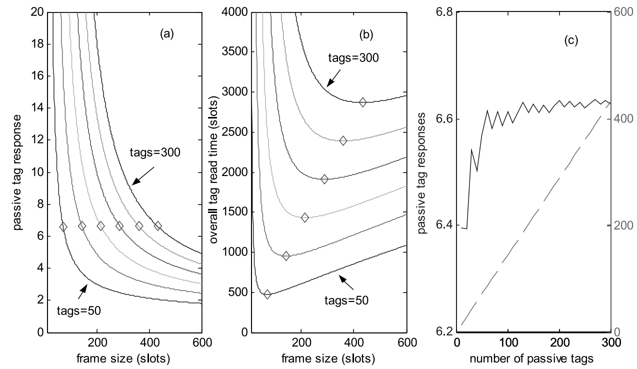


Fig. 3 Passive tags reading using static frame size ($\alpha = 0.99$): (a) expected collection rounds, (b) overall tag read time, and (c) frame size (dashed line) and corresponding read cycles (solid line) to reach minimum of overall passive tag read time.

Therefore, for a fixed passive tag set n, static frame size N, it should be at least

$$R_{p\_f} \geq \log(1-\alpha)/\log(1 - Np_1/n) \tag{3}$$

frames to achieve confidence level α. Obviously, the R_{p_f} decreases monotonously with an increment in N. This means increasing the frame size always reduces the tag responses. The least overall passive tag read time,

$$R_{p\_t\_\min} = \min(N^* R_{p\_f}), \tag{4}$$

can be achieved with the optimum frame size N_{min_p}. Figures 3(a) and (b) compute the expected collection rounds and overall passive tags read time which is normalized by the slot size. The passive tags are from 50 to 300 with a step of 50, the static frame sizes are from 10 to 600 with a step of 1, and the confidence level $\alpha = 0.99$. With increment in the frame size, the overall read time reduces sharply to its minimum and then increases slowly. Figure 3(b) shows that two frame sizes can meet with the same overall collection delay requirement. The shorter one is located in the unstable area of slotted ALOHA, while the longer one is in the stable area and gives fewer expected tag responses [14]. This indicates that it is better to somewhat overestimate the tag set without much expense on the overall read time. Figure 3(c) redraws the optimal frame size and the corresponding expected read cycles to achieve the minimum of overall passive tag read time, which appear as diamond shape in Figs. 3(a) and (b). With the optimal frame size $N_{min\_p} = 1.4^* n$, the needed tag responses $R_{p\_t\_min} \approx 6.6$ to reach $\alpha = 0.99$ assurance level.

The same analysis can be conducted on the active RFID systems. Since the successful active tags are put into Sleep state, the number of active tags in the $(i+1)$th read cycle are equal to or fewer than those in the current collection,

$$n(i+1) = n(i) - p_1(i) * N(i). \tag{5}$$

Fewer tag responses reduce the tag collision probability in the next collection round. Given active tag set n, the collection rounds to read all tags R_{a_f} can be solved from Eq. (2). The minimum average overall active tag read time is given

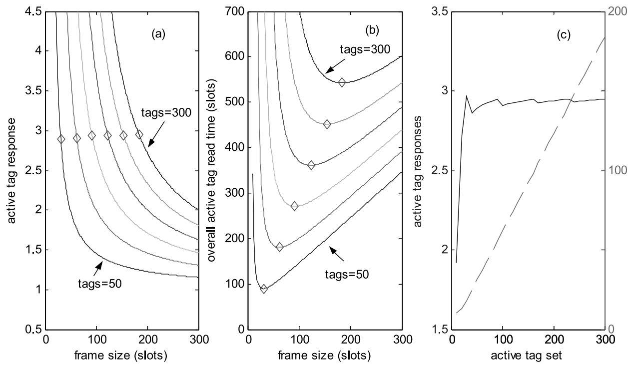


Fig. 4 Active tags reading using static frame size: (a) expected tag responses, (b) overall tag read time, and (c) frame size (dashed line) and corresponding expected tag responses (solid line) when the least overall active tag read time is achieved.

by

$$R_{a\_t\_\min} = \min\left(\frac{\sum_{i=1}^{R_{a\_f}} N(i) * p_1(i) * \sum_{j=1}^{i} N(j)}{n}\right). \tag{6}$$

Figures 4(a) and (b) depict the expected active tag responses and the overall active tag read time. The active tags are from 50 to 300 with a step of 50. The frame sizes are from 10 to 300 with a step of 1. Labeled in diamond shape, the frame size to achieve the least overall read time is $N_{min\_a} = 0.65 * n$ and the corresponding average active tag response is $R_{a\_t\_min} \approx 3$. We draw them again in Fig. 4(c). In Figs. 4(a) and (b), we can see that the downward rate of R_{a_t} is much larger than the upward rate of R_{a_f} in the neighbour area of $R_{a\_t\_min}$. This means more battery power can be saved with little expense on overall read time. For example, given an active tag set of 300, when we use a frame size of $N = n$, compared with those achieving the least read time, the overall tag read time increases by 12.4%, while the needed tag responses reduces as much as 33.3%.

3.2 Channel and Capture Effect

The above analysis are based on the assumption that when two or more packets collide all packets are lost. However, a realistic radio receiver is able to capture the strongest or the earliest of the overlapped packets. This is known as capture effect [10], [12], [13]. The probability of capture effect occurs when packets collide in a slot is given by the power difference between the received packets [13]

$$F_{zq}(z_0) = prob\{P_s/P_q > z_0\}, \tag{7}$$

with z_0 as the capture ratio, P_s and P_q as the power of concerned signal and summary power of all associated interference signals. When z_0=1, the perfect capture effect, which means one packet will be correctly received no matter how much packets overlap. According to Eq. (1) and Eq. (7), the probability of being able to capture receiver in a slot is given by

$$p_{cap} = \sum_{q=1}^{n} p_q F_{zd}(z_0). \tag{8}$$

For active RFID tags and backscattered passive RFID tags operating at UHF and microwave frequency band, the interrogation range of reader is less than few hundreds meters and the mobility of tagged objects is usually limited to walking speed. The dominant effect of uplink channel can be characterized by Rician fading or Rayleigh fading depend on if the direct LOS path between tag and reader exists or not [13], [16]. In a pure Rayleigh fading wireless environment where the concerned tags and interferer tags are far from the reader and without LOS path to reader, the slot capture probability can be given by [13]

$$F_{zq\_Rl}(z_0) = \frac{1}{qz_0 + 1}. \tag{9}$$

When the direct LOS path exists between the concerned tag and reader and the interference from other tags are Rayligh distribution, the capture probability over Rician fading channel can be expressed as [13], [16]

$$F_{zq\_Rc}(z_0) = e^{-qK} e^{-Az_0} \sum_{i=1}^{\infty} \frac{(qK)^i}{i!} \sum_{k=0}^{q-1+i} \frac{(Az_0)^k}{k!}, \tag{10}$$

where $K = \frac{p_d}{\bar{p}_s}$ is Rice factor defined as the ratio between average direct power p_d and average scattered power $\bar{p}_s$ received over scattered paths and $A = \frac{1+K}{\bar{p}_s + p_d}$. In the case of pure log-normal shadowing, the capture probability becomes [13]

$$F_{zq\_S}(z_0) = \frac{q+1}{\sqrt{2\pi}} \int_{-\infty}^{L_1} \exp(-u^2/2)du. \tag{11}$$

where $L_1 = \frac{[m_d - m_u - \ln(z_0)]}{\sigma^2 + \sigma_u^2}$. Here, $\exp(m_d)$ is the area mean power of desired signal, σ_u^2 and $\exp(m_u)$ are the logarithmic variance and area mean of a log-normal variable which is approximately equivalent to the sum of n independents log-normal components. The σ_u^2 and m_u can be determined recursively as in [13]. The near-far effect is described by expressing area mean power as

$$\xi = r^{-\gamma}. \tag{12}$$

where r is the normalized distance from tag to reader relative to the maximal distance between them and γ is the path-loss law exponent for the radio channel, which lie in the range of 2–5 depending on the indoor and outdoor environment [13].

The capture effect increases the probability of good tag ID reception in a slot. On the other hand, it reduces the number of estimated tags since some slot collision detections are skipped over. Figure 5 compares the passive tag reading to achieve the least read time in a pure Rayleigh and Rician fading environment with different z_0. Generally, the capture effect reduces overall tag reading time with more tag responses and shorter frame size. In the case of Rician fading (z_0=1, K=2, A=3), the optimal frame size $N_{min\_p} = n$, and the needed tag responses increase to $R_{p\_t\_min} \approx 7.8$. With the

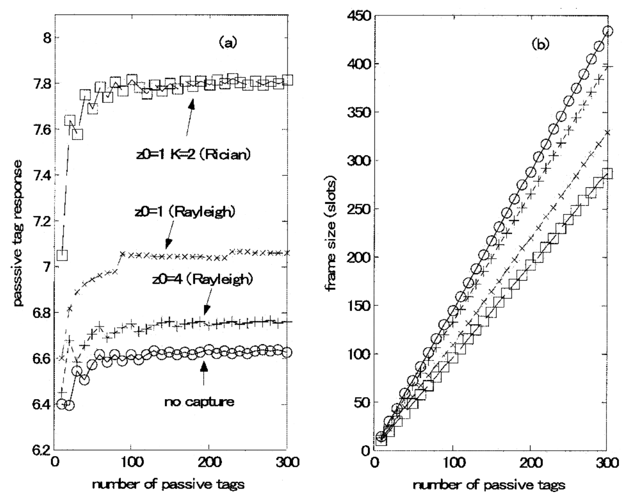


Fig. 5 Passive tag reading to achieve the least read time in Rayleigh and Rician fading channel with capture ($\alpha = 0.99$): (a) number of passive tag responses; and (b) frame size.

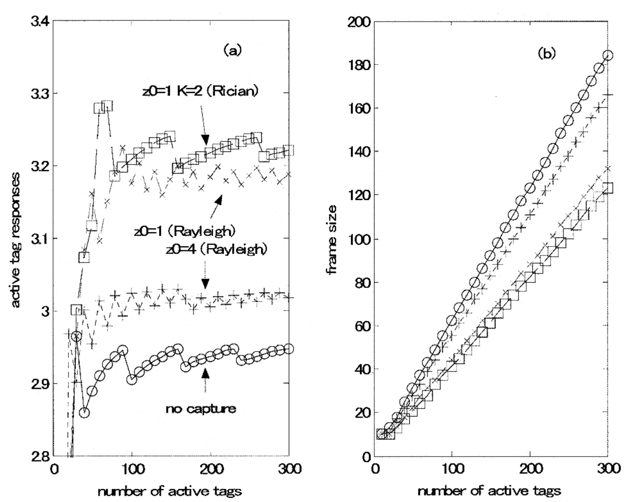


Fig. 6 Active tag reading to achieve the least read time in Rayleigh and Rician fading channel with capture: (a) number of active tag responses; and (b) frame size.

same z_0, the capture probability over Rician fading channel is larger that that over Rayleigh fading channel since the direct path usually yields the strongest signal. The same tendency can be observed in Fig. 6 which draws the active tag reading in the same channel conditions. In the Rician fading channel, the frame size to achieve the least overall read time is $N_{min\_a} = 0.45n$ and average active tag response increases to $R_{a\_t\_min} \approx 3.2$. Again, we can save more battery power at little expense on the overall reading time. Given n=300 and z_0=4 in a pure Rayleigh fading channel, when we use a frame size of $N = 0.8n$, compared with those to achieve the least tag read time, the overall tag read time increases by 14.3% and the tag responses reduces as much as 37.1%.

3.3 Dynamic Frame Size Analysis

In typical applications of the RFID systems, usually the tag set is unknown in advance and can vary in a large dynamic range [1]. A dynamic frame size control is therefore necessary. The dynamic ID collection procedure starts from a coarse estimation of the tag set, usually a fixed initial frame size and update frame size in the next collection round [8], [9]. In the ith collection round, we can observe g garbled slots, s successful slots and e empty slots. For an observed slot, the *a posteriori* probability distribution of k tags choosing the slot is

$$p_k^0(i) = \begin{cases} 0 & \text{if } k = 0, 1 \\ \dfrac{p_k(i)}{1 - p_0(i) - p_1(i)} & \text{if } k \geq 2 \end{cases} . \tag{13}$$

In other words, the *a posteriori* expected value of the number of tags is respectively, 0 for an empty slot, 1 for a success slot, and $\sum_{k=2}^{N} kp_k^0(i)$ tags for a garbled slot. Therefore, the estimated tag sets in the current collection round is $p_1(i) + \sum_{k=2}^{N} kp_k^0(i)$. Since we have no prior information on tag sets before and during tag identification, we make a simple guess about the tag number present from the outcome of the ith read cycle,

$$n_{est}(i+1) = s + Kg, \tag{14}$$

where $K = \lim_{N\to\infty} \sum_{k=2}^{N} kp_k^0(i) = 2.39$ is a constant value for garbled slots [11]. On estimating the tag set in the ith collection round, as per analysis in the last section the frame size in the $(i+1)$th collection round is

$$N(i+1) = H * n_{est}(i+1)$$
$$\begin{cases} H = 1\text{–}1.4 & \text{passive tag} \\ H = 0.8\text{–}1 & \text{active tag} \end{cases} , \tag{15}$$

where H is a constant mapping the tag set to the frame size depend on whether tags are active or passive, channel conditions, and capture ratio of receiver at reader. As per the analysis in the last section, although H=0.8–1 used in active tag increase the overall read time, the battery energy consumption are greatly reduced.

To combat random jitter during ID collection, a threshold $\gamma = 1.15$ is defined. The frame size update occurs only when $n_{est}(i+1) \geq \gamma * n_{est}(i)$. The total dynamic ID collection procedure is summarized as follows.

```
Dynamic_identification {
  N = 16 or 20; //depend on active tag or passive tag†
  i = 0; //counter of collection round given a frame size
  do {
    i++;
    [g, s]= perform_read_cycle(N);
    n_est(i) = estimate_tag_set(N,g,s); // as per Eq. (14)
    if n_est(i) > γ * n_est(i − 1) { // start a new frame size and
    reset
```

†See next section for initial frame size.

N = dynamic_frame_size(n_{est}(i)); // as per Eq. (15),
$i = 0$;}
}while ($i < R_{p\_f}$ or R_{a_f}); // read all tags with confidence level
}

4. Multiple RFID Read Simulation

In this section, we simulate the case where there is no capture since the only difference between the two cases is the coefficient in Eq. (15) which map tag set to frame size.

First, static frame size simulations were conducted to verify the above analysis. We simulated tag set from 10 to 120 tags with a step of 5, while the static frame size was from 10 to 160 with a step of 5. Each simulation was run 500 times. For example, Fig. 7 compares the simulation and the analysis obtained from Eq. (4) and Eq. (6). The passive tag set was 30 and the active tag set was 80, respectively. Well agreements were obtained. From overall tag read time, the frame sizes to achieve the minimum and the corresponding collection rounds can be obtained. Figure 8 compares the simulations and theoretical results obtained from Eq. (2) to Eq. (6), including both active tags and passive tags.

Furthermore, dynamic frame size simulations were conducted on more realistic identification scenarios. Table 1 lists the parameters for both the active and passive RFID system, including duration of reader-tag commands and tag-reader responses. The former parameters are from ISO/IEC 18000-7 draft [9]. Philip's I-Code system was used as a typical example of a passive RFID system [8], [14]. With passive tags, the performance is measured by overall tag read time only. With active tags, the performance measurements consist of overall tag read time and tag responses (power consumption). Whenever changing to a new frame size, $R_{p\_f\_min} = 8$ read cycles must be performed for passive tags to reach $\alpha = 99\%$. Reading all active tags can be guaranteed until we receive no more responses in a read cycle. The Wakeup signal is not considered in the simulation [9]. The initial frame sizes were set to respectively, 20 slots and 16 slots for active tags and passive tags.

The simulation results on dynamic frame size were sketched in Fig. 9 and Fig. 10. In Fig. 9, applied to passive tags, we can see that the proposed scheme (denoted as "PTD_rnd") outperforms H. Vogt's scheme† (denoted as "vogt") in both overall read time and tag responses, especially in the case of a large tag set. Compared with Vogt's scheme, the overall read time was reduced by 31.3% on average except when tag sets are 20 and 25. To simplify the passive tag, we limited the frame size to be one of 16, 32, 64, 128, or 256 as in Philip's I-Code system [8], [14]. As denoted by "PTD_bin," the overall tag read time was reduced by 23.2% on average. Total 120 tags could be read within 10 seconds. Good tag set estimation was obtained af-

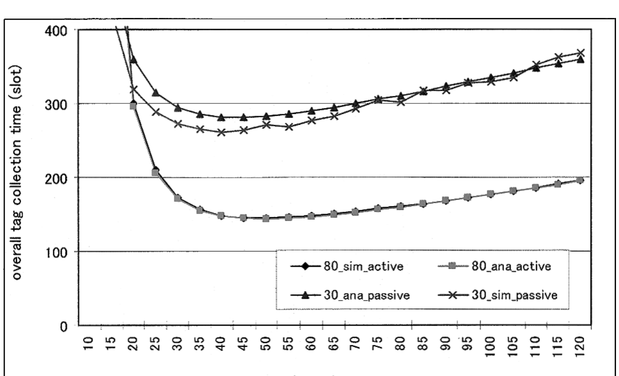


Fig. 7 Overall tag read time using static frame size.

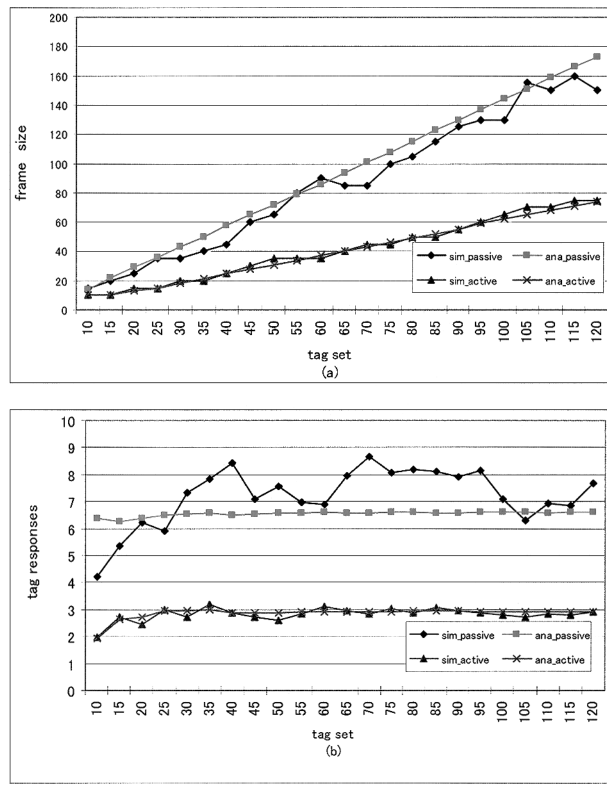


Fig. 8 (a) Static frame size and (b) the corresponding collection rounds to achieve minimal overall tag read time when using static frame size.

Table 1 Simulation parameters.

Tags	Command and data	Time (ms)
Active RFID system	Collect (reader → tags)	4.224
	Tag response (tags → reader)	5.364
	Sleep (reader → tags)	4.512
Passive RFID system	Collect (reader → tags)	52
	Tag response (tags → reader)	5

†The frame sizes were obtained from Fig. 2 of [8].

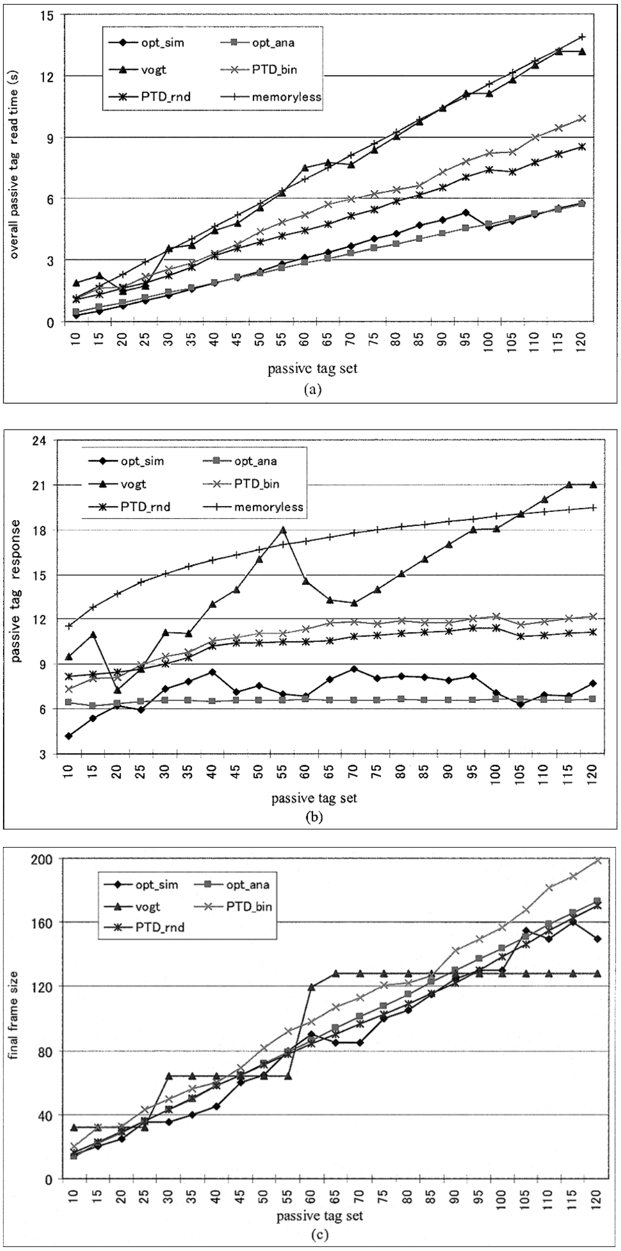


Fig. 9 Passive tag read performance using dynamic frame size: (a) overall tag read, (b) passive tag response, and (c) final frame size. The legends are as follow: "opt_sim" denotes the optimal results for given tag set; "opt_ana" denotes the theoretical optimization; "vogt" denotes H. Vogt's tag set estimation [8]; "PTD_rnd" denotes passive tag set dynamic estimation as per Eq. (15); "PTD_bin" is the same as "PTD_rnd" expect that the frame size must be from set (16,32, 64, 128, 256); and "memoryless" denotes deterministic scheme from C. Law [7].

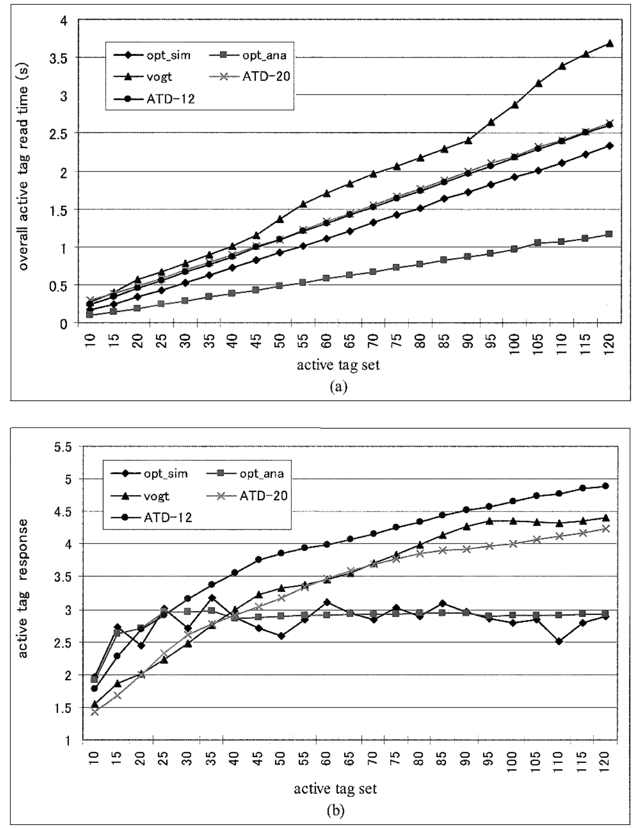


Fig. 10 Active tag read performance using dynamic frame size: (a) overall tag read time, and (b) tag response. The legends are as follow: "ATD-20" and "ATD-12" denotes active tag set dynamic estimation as per Eq. (15) with initial frame size of 20 slots and 12 slots.

ter 4 collection rounds. H. Vogt's scheme suffers from slow frame size update and small frame size. The frame sizes listed in Table 3 of [8] are not optimal for the corresponding tag sets. Performance of memoryless protocol was also shown in Fig. 9 [7]. The long overall tag reading time results from too many tag responses. As shown in Fig. 9(c), the final estimated frame sizes were larger than the optimal frame sizes. This gave us more confidence on identification results. The legends "opt_xxx" denoted the optimized values through simulation and analysis when the tag sets are known in advance.

Compared with H. Vogt's scheme, applying the proposed scheme to the active tag (denoted as "ATD_xx") reduced the overall tag read time by 17.6% and the tag response by 3% on average. Figure 10 also compares different initial frame sizes with the same update parameters in Eq. (14). The draft of ISO/IEC 18000-7 recommended a fixed initial frame size of 12 slots [9]†. Although there was almost no difference in overall tag read time, over 10% of tag responses were saved by using 20 as the initial frame size. An active tag set of 120 can be read within 2.64 seconds with an average 4.25 tag responses.

5. Discussion and Conclusions

The major feature of framed ALOHA distinguishing from standard slotted ALOHA is that a terminal is permitted to send only one packet in a frame. The framed ALOHA matches the Reader-Talk-First mode of RFID system where

†In ISO/IEC 18000-7 draft, a tag response consists of tag status, message length, Int ID, tag ID, owner ID and CRC. The total responses 14 bytes and lasts approximate 5.36 ms [9]. The fixed initial frame duration is 57.3 ms. That is about 12 slots.

the reader is the network control center. Originating in the communication field, the main aim of slotted ALOHA is to maximize the system throughput [11]–[13]. The greatest throughput is achieved when the number of node/packets is equal to the frame size. In RFID field, we care more about tag read accuracy, overall tag read time and lifetime of tags [1], [4]. As shown in Fig. 3 to Fig. 6, the parameters set to achieve the greatest throughput cannot make the least overall reading time for both passive and active tags. The frame sizes for passive tags to achieve the least tag read time are larger than those to achieve the maximum throughput, whereas those of active tags are smaller than them. For applications of continuous tag reading, e.g. in a supply chain and product line, all of reading rate, accuracy and tag lifetime are important. Figure 3 to Fig. 6 show the tradeoff among access delay, accuracy and energy consumption. Also, Eq. (4) and Eq. (6) limit the performance boundary given a tag set.

The fading in active RFID system is similar to that in the cellular communication system. In the backscattered passive RFID systems at UHF and microwave frequency band, fading comes from both downlink energy feed and uplink transmission. In the downlink from reader to tags, the injected electromagnetic field arrive the tag directly or through reflection by objects in its vicinity. All fields are superimposed at the tag. This leads to a local damping and amplification of the field at interval of half of wavelength between the neighbor minima. Such effect is expected particularly in an environment containing large metal objects, e.g. in an industry operation (machines, metal pipe etc.). That is tags could have different injected field energy even when they are the same distance from a reader. It is the same in the uplink, the reflected signals from a tag arrive the reader through different paths. Many simultaneous individual reflections of varying intensity and delay are superimposed at antenna of the reader.

Compared with deterministic methods, one of the benefits of statistical methods is fast reading. A drawback is that it cannot guarantee 100% of the recognition rate. However, this is only true without considering the capture effect. In statistical methods, a packet transmission is received despite collisions and the "missed" tags wait for the next chance to be read. But, using deterministic methods, the "missed" tags are lost forever since their voice is buried by the same strong signals. Therefore, the deterministic methods cannot realize 100% of recognition as claimed. Floerkemeier reported capture effect when using I-code passive tags [15]. One of the solutions to this issue is the Manchester channel coding with On-Off Keying (OOK) modulation. Logical "0" or "1" from tag is located in two different time slots. As shown in Fig. 11, during the transmission of either logical "0" or "1," there is no modulation over the channel in a time slot. When the same logical value conflicts with each other, the reader can read the received bits correctly as the tag response are synchronized. When a logical "0" conflicts with "1," both the time slots are filled with signal without overlap in time. The reader can recover signal from both slots and know the

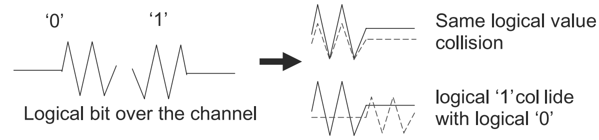


Fig. 11 Manchester coding of data and OOK modulation.

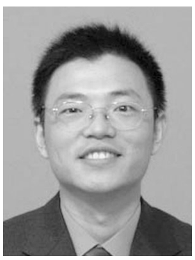
occurrence of packet collision. It does not matter the signal strength difference between them. The anti-collision algorithm can then split the tree and query again.

Although framed ALOHA is simple, slot clock is needed. Usually, active tags carry clocking circuit at the tag side, while time slot is segmented by the reader for passive tags. In conclusion, we investigated how to optimize tag responses as well as overall tag collection time using framed ALOHA to identify multiple RFID tags without prior information on tag set. A combinatory model was presented for both active and passive tags. The capture effect of receiver over Rician and Rayleigh fading channel was considered. By using the model, we made a good estimation of the tag set and a fast frame size update. The theoretical analysis was in good agreement to simulations. We came up that 20 is a better initial frame size for active RFID systems. In addition, we proposed to use Manchester channel coding with OOK modulation to combat capture effect in deterministic anti-collision algorithms.

References

[1] K.F. Kenzeller, RFID Handbook, 2nd ed., Wiley Press, 2003.
[2] V. Stanford, "Pervasive computing goes to the last hundred feet with RFID system," IEEE Pervasive Comput., vol.2, no.2, pp.9–14, 2003.
[3] S.E. Sarma, "Towards the five-cent tag," Technical Report, MIT-AUTOID-WH-006, MIT Auto-ID Center, 2001.
[4] I. Chlamtac, C. Petrioli, and J. Redi, "Energy-conserving access protocols for identification networks," IEEE/ACM Trans. Netw., vol.7, no.1, pp.51–59, Feb. 1999.
[5] D.R. Hush and C. Wood, "Analysis of tree algorithms for RFID arbitration," IEEE Inter. Sym. on Information Theory, p.107, 1998.
[6] C. Law, K. Lee, and K. Siu, "Efficient memoryless protocol for tag identification," Tech. Rep. of MIT Auto-ID Center, MIT-AUTOID-TR-003.pdf, 2000.
[7] M. Jacomet, A. Ehrsam, and U. Gehrig, "Contactless identification device with anticollision algorithm," IEEE Conf. on Circuits, System, Computers and Communications, pp.4–8, Athens, 1999.
[8] H. Vogt, "Efficient object identification with passive RFID tags," Inter. Conf. on Pervasive Computing, LNCS, pp.98–113, Springer-Verlag, 2002.
[9] ISO/IEC 18000-7 draft, "RFID for item management—Air interface, Part 7—Parameters for an active RFID interface communications at 433 MHz," (684_18000-7_FCD.doc at http://www.autoid.org)
[10] D.W. Engels, "The reader collision problem," Tech. Rep. of MIT Auto-ID Center, MIT-AUTOID-WH-007.pdf, 2002.
[11] F.C. Schoute, "Dynamic frame length ALOHA," IEEE Trans. Commun., vol.31, no.4, pp.565–568, 1983.
[12] J.E. Wieselthier, A. Ephremides, and L.A. Michaels, "An exact analysis and performance evaluation of framed ALOHA with capture," IEEE Trans. Commun., vol.37, no.2, pp.125–137, 1999.
[13] R. Prasad, Universal Wireless Personal Communications, Artech House, 1998.
[14] http://semiconductors.phlips.com/markets/identification/products/icode

[15] C. Floerkemeier and M. Lampe, "Issues with RFID usage in ubiquitous computing applications," 2nd Inter. Conf. on Pervasive Computing, Vienna, Austria, 2004.
[16] J. Sanche and D.R. Smith, "Capture effect in Rician fading channels with application to slotted ALOHA," IEEE Globecom, pp.2390–2394, Roi de Janeiro, Brazil, 1999.



Bin Zhen is a research associate at NTT Network Innovation Laboratories from 2003, where he currently works on performance improvement of active RFIDs. Before this, he was with the i-Network Lab of Samsung Advanced Institute of Technology. His conducted research on wireless personal area networks, e.g. Bluetooth and WiMedia. He received his Ph.D. in biomedical engineering and M.S. degree in electronic engineering from Xi an Jiaotong University, Xi an, China in 1997 and 1994, respectively. His present research interests involve random access of mobile network and low-power ad hoc network design.

Mamoru Kobayashi received his B.E. and M.E. degrees in electronic engineering from Shizuoka University, Shizuoka in 1987 and 1989, respectively. In 1989, he joined NTT Wireless System Laboratories in Yokosuka, Japan. Since then, he has been engaged in research on channel control for satellite communications systems. He is now a senior engineer in the research group for active RFIDs and related applications.

Masashi Shimizu is a senior research engineer and supervisor at NTT Wireless System Laboratories in Yokosuka, Japan. He received his B.E. and M.E. degrees in mechanical engineering from Keio University, Yokohama in 1986 and 1988, respectively. He joined NTT in 1988. Since then, he has been engaged in research on the pointing control for deployable space antennas and surface error compensation through feed distribution control. His recent interests focus on active RFIDs and related applications.