Randomized Scheme for Cognizing Tags in RFID Networks and Its Optimization

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Abstract

An RFID network is a network in which a reader inquire about the identities of tags and tags respond with their identities to a reader. The diversity of RFID networks has brought about many applications including an inexpensive system where a single reader supports a small number of tags. Such a system needs a tag cognizance scheme that is able to arbitrate among contending tags as well as is simple enough. In this paper, confining our attention to a clan of simple schemes, we propose a randomized scheme with aiming at enhancing the tag cognizance rate than a conventional scheme. Then, we derive an exact expression for the cognizance rate attained by the randomized scheme. Unfortunately, the exact expression is not so tractable as to optimize the randomized scheme. As an alternative way, we develop an upper bound on the tag cognizance rate. In a closed form, we then obtain a nearly optimal value for a key design parameter, which maximizes the upper bound. Numerical examples confirm that the randomized scheme is able to dominate the conventional scheme in cognizance rate by employing a nearly optimal value. Furthermore, they reveal that the randomized scheme is robust to the fallacy that the reader believes or guesses a wrong number of neighboring tags.

Keywords: RFID networks, framed and slotted ALOHA, tag cognizance scheme, exact expression for tag cognizance rate, nearly optimal value for probability of seizing an opportunity

1. Introduction

Radio frequency identification (RFID) network is a network which consists of readers and tags. In an RFID network, a reader, in a contactless fashion, acquires information stored at a tag by using radio waves [1-2]. Technological development has enabled a tag to communicate with a reader in either low frequency (LF) band, mid frequency (MF) band or ultra high frequency (UHF) band. Also, tags have been improved to work not only actively, i.e., by internal power source but also passively, i.e., by being powered from a reader in a wireless fashion. Such a diversity enabled RFID networks to be easily adopted in many applications including tracking animals, paying by contactless smart cards and managing items. In addition, International Organization for Standardization (ISO) and EPCglobal released a number of standards regarding RFID networks [1-2].

Typically, in an RFID network consisting of passive tags, a reader inquires about the identities of neighboring tags and a tag responds to the inquiry of a reader. If only one tag responds and a reader successfully receives the response, the reader definitely cognizes the tag. However, two or more tags may simultaneously respond to the inquiry of a reader, i.e., they may transmit packets containing their identities at the same time. Then, the packets collide and the reader is hardly able to cognize any tag involved in the collision.

In the last decade, many efforts have been made to cognize a tag while arbitrating a packet collision [3-5]. The efforts resulted in numerous tag cognizance schemes, which are categorized into two tribes; one is a tribe of the schemes rooted in framed and slotted ALOHA [6-24] and the other is a tribe of the schemes rooted in m-ary tree scheme [25-33]. Usually, a tag cognizance scheme, which belongs to the tribe rooted in framed and slotted ALOHA, employs a time structure in which time is divided into frames and each frame contains a prescribed number of slots. In such a time structure, a tag randomly (especially, equally likely) chooses a slot in a frame and then responds with its identity during the selected slot. According to whether a tag which has been already cognized by the reader is prohibited from responding afterwards or not, the tag cognizance schemes are classified into a clan of restricted schemes [16][18] and a clan of unrestricted schemes [9][17][19][22]. Also, depending on whether the number of slots contained in each frame is fixed or varied, the tag cognizance schemes are divided into a clan of static schemes [9] and a clan of dynamic schemes [13][17][22]. A tag cognizance scheme belonging to the dynamic clan usually requires the information about the number of tags residing in the vicinity of the reader. Upon such a demand, various methods have been released for estimating the number of neighboring tags [7][10][14][17][22].

Compared with the unrestricted clan, the restricted clan is able to reduce the population of the tags which contend to respond. Thus, the probability that two or more tags respond simultaneously can be decreased, and consequently, the tag cognizance rate can be enhanced. In each frame, however, the reader may have to inform a tag of whether it was already cognized or not. As a result, the complexity is increased at the expense of the improvement in tag cognizance rate. Meanwhile, the dynamic clan may find an optimal number of slots per frame which maximizes the tag cognizance rate. However, such an optimization must be based on continual estimations of the number of neighboring tags. Thus, the dynamic clan bears higher complexity than the static clan. Both of the restricted clan and the dynamic clan may be excessively complicated or sophisticated for an RFID network that supports a relatively small number of tags. Also, these clans may be inappropriate for inexpensive applications which can not endure economic burdens brought by high complexity.

In this paper, bearing in mind inexpensive applications that support only a few tags, we confine our attention to the tag cognizance schemes which belong to the unrestricted as well as static clan. Conventionally, a tag cognizance scheme belonging to such a clan chooses a single slot in a frame and responds during the selected slot. Aiming at improving the tag cognizance rate while not losing simplicity, we propose a randomized scheme, where a tag is able to choose multiple slots in a probabilistic fashion and repeats responding in each selected slot. Then, we derive an exact expression for the cognizance rate attained by the randomized scheme. The cognizance rate can be maximized by employing an optimal value for a key design parameter called probability of seizing an opportunity. Unfortunately, the exact expression for the cognizance rate is not so tractable as to find such an optimal value in an analytical fashion. As an alternative way, we present a tight upper bound on the cognizance rate and yield an exact expression for the upper bound. In a closed form, we then obtain a nearly optimal value for the probability of seizing an opportunity, which maximizes the upper bound rather than the cognizance rate itself. Finally, we provide numerical examples on the cognizance rate achieved by the randomized scheme. Through the examples, we demonstrate a high precision of the nearly optimal value by adopting a measure called relative change. Also, we confirm that the randomized scheme, which employs a nearly optimal value for the probability of seizing an opportunity, is able to dominate the conventional scheme in cognizance rate. Furthermore, we reveal that the randomized scheme is robust to the fallacy that the reader believes or guesses a wrong number of neighboring tags.

In section 2, we propose and describe a randomized scheme for cognizing tags. In section 3, we derive an exact expression for the cognizance rate achieved by the randomized scheme. In section 4, we present an upper bound on the cognizance rate and find an exact expression for the upper bound. In a closed form, we then obtain an exact expression for the nearly optimal value (for the probability of seizing an opportunity) which maximizes the upper bound rather than the cognizance rate itself. Section 5 is devoted to numerical examples, which demonstrate a high precision of the nearly optimal value, dominance of the randomized scheme in cognizance rate and robustness of the randomized scheme to a lack of information about the number of tags.

2. Randomized Scheme

In this section, we consider an RFID network which consists of a single reader and many tags residing in the vicinity of the reader. (See **Fig. 1**) Then, we propose a randomized scheme for the reader to cognize tags and describe the details of the scheme.

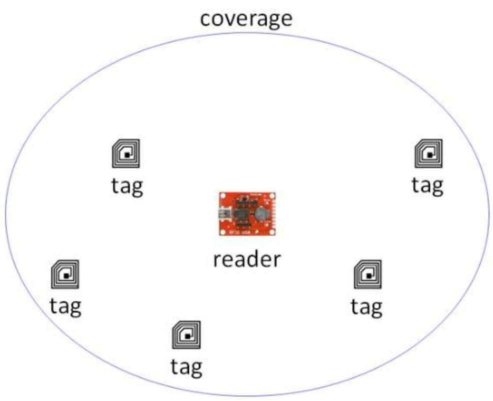


Fig. 1. Configuration of RFID network.

In the randomized scheme, as shown in **Fig. 2**, time is divided into frames. Then, a frame is partitioned into an inquiry part and a response part. Also, a response part is divided into a prescribed number of slots. (A slot is a time interval in which a tag is able to transmit a packet containing the identity of the tag.)

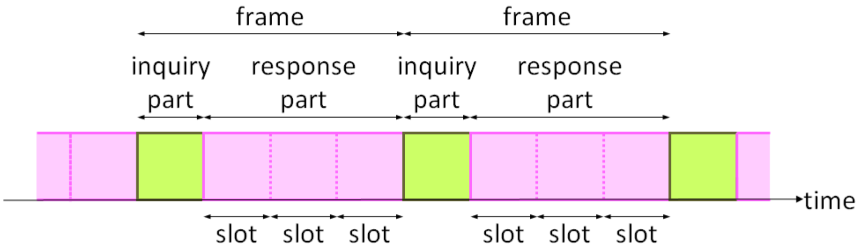


Fig. 2. Time structure in randomized scheme.

On such a time structure, the randomized scheme behaves as follows: First, the reader inquires about the identities of neighboring tags using the inquiry part of a frame. Secondly, upon reception of the inquiry, a tag selects a number of slots to send a packet containing the identity of the tag. For this purpose, a prescribed number of opportunities are provided to a tag. (Let K denote the number of opportunities.) At each opportunity, the tag seizes the opportunity with probability $p \in (0,1]$ while it passes up the opportunity with probability $1 - p$. Once the tag seizes the opportunity, it equally likely selects a slot among the slots contained in the response part. Thirdly, the tag repeats responding with a packet (which encapsulates the identity of the tag) in the selected slots of the response part. Note that a slot may be selected multiple times. In such a case, however, the tag responds in the slot only once. **Fig. 3** summarizes the behaviors of the reader and tags according to the randomized rule.

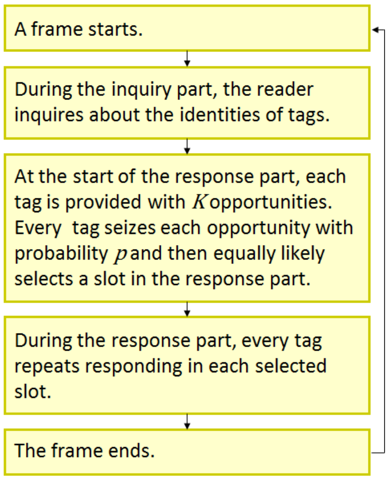


Fig. 3. Behaviors of reader and tags according to randomized scheme.

3. Analysis of Cognizance Rate

The cognizance rate is roughly defined by the average number of tags that the reader cognizes per unit time. The cognizance rate is a major performance measure for evaluating tag cognizance schemes. In this section, we derive an exact expression for the cognizance rate attained by the randomized scheme. For this purpose, we consider an RFID network in which M tags, denoted by $\tau_1, \cdots, \tau_M$, are scattered around a single reader. In the network, time is divided into frames. Also, a frame is partitioned into inquiry part and response part, where the length of the inquiry part is equal to the duration of $A \in \mathbb{N}$ slots and the response part consists of $B \in \mathbb{N}$ slots.

3.1 Conventional Scheme

In this section, for a comparative evaluation of the randomized scheme, we consider a conventional scheme in the restricted as well as static clan. Then, we derive an exact expression for the cognizance rate achieved by the conventional scheme. In the conventional scheme, every tag equally likely selects a slot in each frame. Then, all the tags respond during their selected slots, respectively. Let X_n denote the number of tags that the reader cognizes during the nth frame for $n \in \{1, 2, \cdots\}$. Then, the cognizance rate achieved by the conventional scheme, denoted by ρ_C, is defined as follows.

$$\rho_C = \lim_{n\to\infty} \frac{X_1 + \cdots + X_n}{(A+B)n} \tag{1}$$

in tags/slot. Since $X_1, X_2, \cdots$ are independent and identically distributed, the cognizance rate is yielded by

$$\rho_C = \frac{E(X_n)}{A+B} \tag{2}$$

from the strong law of large numbers [34]. Note that X_n is equivalent to the number of boxes filled with only one ball when M balls are equally likely put into B boxes [35]. The following theorem shows an exact expression for the cognizance rate achieved by the conventional scheme.

Theorem 1. The cognizance rate achieved by the conventional scheme

$$\rho_C = \frac{M}{A+B}(1 - \frac{1}{B})^{M-1} \tag{3}$$

in tags/slot.

The proof of the theorem is given in the appendix.

3.2 Randomized Scheme

In the randomized scheme, as described in section 2, a tag is afforded K opportunities for making a selection of a slot in each frame. Then, the tag seizes an opportunity with probability p. Let X_n represent the number of tags that the reader cognizes during the nth frame. Then, the cognizance rate attained by the randomized scheme, denoted by ρ_R, is defined by

$$\rho_R \triangleq \lim_{n\to\infty} \frac{X_1 + \cdots + X_n}{n(A+B)} \tag{4}$$

in tags/slot. Since $X_1, X_2, \cdots$ are mutually independent and identically distributed,

$$\rho_R = \frac{E(X_n)}{A+B} \tag{5}$$

by the strong law of large numbers [34].

Differently from the conventional scheme, the randomized scheme allows a reader to cognize a same tag many times in a frame. Considering such a difference, we obtain the expected value of X_n as follows. Let S_{mn} denote the number of slots in which the tag τ_m responds during the nth frame. Let R_{mn} denote the number of slots in which the reader cognizes the tag τ_m. Then, $R_{mn} \le S_{mn}$ obviously. Set

$$U_{mn} \triangleq I_{\{R_{mn} \ge 1\}} \tag{6}$$

for $m \in \{1, \cdots, M\}$, where I_C is the indicator function such that

$$I_C = \begin{cases} 1 & \text{if } C \text{ is true} \\ 0 & \text{otherwise.} \end{cases} \tag{7}$$

Since the reader may cognize a same tag in two or more slots during a frame, U_{mn} indicates whether the reader cognizes the tag τ_m or not during the nth frame. Thus, we have

$$X_n = U_{1n} + \cdots + U_{Mn} \tag{8}$$

for $n \in \{1, 2, \cdots\}$. Note that $E(U_{mn}) = P(R_{mn} \ge 1)$ from (6). Also, $E(U_{1n}) = \cdots = E(U_{Mn})$ by symmetry. Thus, the cognizance rate can be rewritten by

$$\rho_R = \frac{MP(R_{mn} \ge 1)}{A+B}. \tag{9}$$

The following theorem shows an exact expression for the cognizance rate attained by the randomized scheme.

Theorem 2. The cognizance rate attained by the randomized scheme

$$\rho_R = \frac{M}{A+B} \sum_{s=1}^{\min\{K,B\}} P(R_{mn} \ge 1 | S_{mn} = s) P(S_{mn} = s) \tag{10}$$

where

$$P(S_{mn} = s) = \binom{B}{s} \sum_{d=0}^{s} (-1)^d \binom{s}{d} \sum_{t=s}^{K} \binom{K}{t} (p\frac{s-d}{B})^t (1-p)^{K-t}$$
$$P(R_{mn} \ge 1 | S_{mn} = s) = \sum_{c=1}^{s} \binom{s}{c} (-1)^{c+1} (1 - p\frac{c}{B})^{K(M-1)}. \tag{11}$$

A proof of the theorem is given in the appendix.

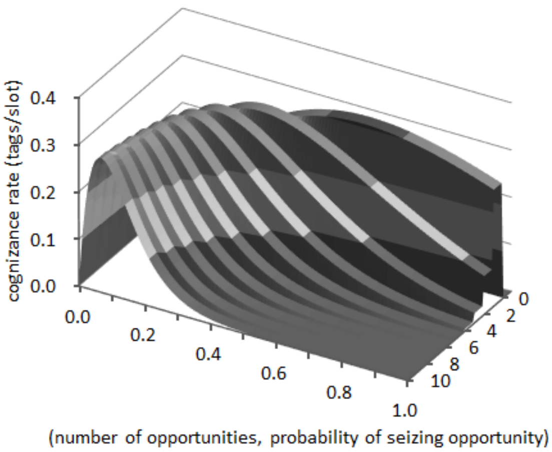


Fig. 4. Cognizance rate attained by randomized scheme vs. number of opportunities and probability of seizing an opportunity.

Fig. 4 shows the cognizance rate attained by the randomized scheme over the space made of the number of opportunities and the probability of seizing an opportunity. In this figure, the number of tags is fixed to 5. Also, the inquiry and response parts are set to be made of 1 and 3 slots, respectively. Given number of opportunities, we observe that the cognizance rate increases until the probability of seizing an opportunity reaches a certain value. However, the cognizance rate rather decreases as the probability of seizing an opportunity is over the value. Such an observation indicates that there is an optimal value for the probability of seizing an opportunity, which maximizes the cognizance rate.

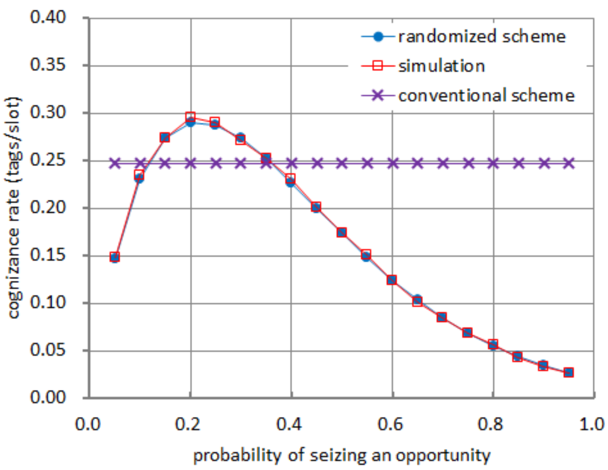


Fig. 5. Cognizance rate vs. probability of seizing an opportunity.

Fig. 5 shows three curves with respect to the probability of seizing an opportunity p. These curves respectively demonstrate (i) the cognizance rate attained by the randomized scheme ρ_R, which is yielded by (10), (ii) an estimate of the cognizance rate $\hat{\rho}_R$, which is obtained by a simulation method and (iii) the cognizance rate achieved by the conventional scheme ρ_C, which is calculated by (3). In this figure, the number of tags is fixed to 5 and the inquiry and response parts are set to be made of 1 and 3 slots, respectively. Also, the number of opportunities is given by 3. In **Fig. 5**, we observe that $\hat{\rho}_R$ almost coincides with ρ_R. In cognizance rate, we also notice that the randomized scheme is able to dominate the conventional scheme by employing a proper value for p. Furthermore, we observe that we can optimize the randomized scheme as to maximize the cognizance rate by adopting an optimal value for p.

Unfortunately, (10) is not so tractable to find an optimal value for p in a closed form. As a result, finding an optimal value for p needs a numerical method. In the next section, we thus seek an alternative way to find a nearly optimal value for p in a closed form.

4. Optimization of Randomized Scheme

To enhance the cognizance rate attained by the randomized scheme, it is of necessity to find an optimal value for the probability of seizing an opportunity. Apparently, it is preferred to obtain the optimal value in a closed form. However, the expression for the cognizance rate in (10) is not so tractable as to obtain an optimal value in a closed form. As an alternative way, we find an upper bound on the cognizance rate and obtain a nearly optimal value for the probability of seizing an opportunity, which maximizes the upper bound rather than the cognizance rate itself, in a closed form. Then, we investigate the precision of the nearly optimal value.

Set

$$Y_n = R_{1n} + \cdots + R_{Mn} \tag{12}$$

for $n \in \{1, 2, \cdots\}$. Then, Y_n represents the number of slots in which the reader cognizes a tag. Note that $Y_1, Y_2, \cdots$ are mutually independent and identically distributed. Recall that X_n represents the number of tags that the reader cognizes during the nth frame. Then, $Y_n \geq X_n$ almost surely since $R_{mn} \geq U_{mn}$ almost surely. Also, $E(Y_n) \geq E(X_n)$. Thus, we have an upper bound on the cognizance rate, denoted by $\bar{\rho}_R$, as follows:

$$\bar{\rho}_R = \frac{E(Y_n)}{A + B}. \tag{13}$$

The following theorem shows an exact expression for the upper bound $\bar{\rho}_R$ in a closed form.

Theorem 3. The upper bound $\bar{\rho}_R$ on the cognizance rate attained by the randomized scheme

$$\bar{\rho}_R = \frac{MB}{A + B}(1 - \frac{p}{B})^{K(M-1)}[1 - (1 - \frac{p}{B})^K]. \tag{14}$$

A proof of the theorem is given in the appendix.

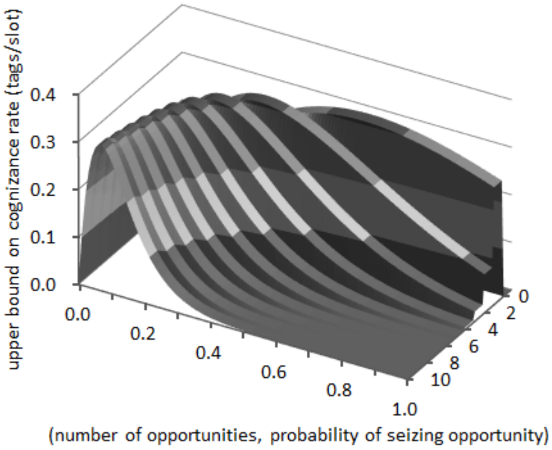


Fig. 6. Upper bound on cognizance rate vs. number of opportunities and probability of seizing an opportunity.

Fig. 6 shows the upper bound on the cognizance rate over the space made of the number of opportunities and the probability of seizing an opportunity. In this figure, the number of tags is fixed to 5. Also, the inquiry and response parts are set to be made of 1 and 3 slots, respectively. Given number of opportunities, the upper bound exhibits a similar tendency as the cognizance rate in **Fig. 4**.

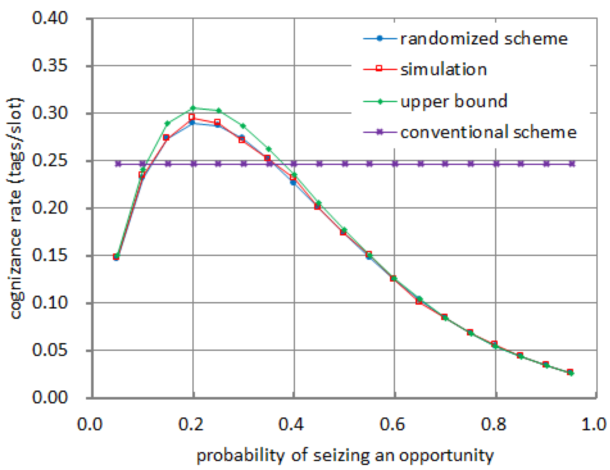


Fig. 7. Cognizance rate and its upper bound vs. probability of seizing an opportunity.

Fig. 7 shows the cognizance rate and its upper bound with respect to the probability of seizing an opportunity. In this figure, the number of tags is fixed to 5 and the inquiry and response parts are set to be made of 1 and 3 slots, respectively. Also, the number of opportunities are set to be 3. We observe that the upper bound is tight. Moreover, we notice that the nearly optimal value, which maximizes the upper bound, is close to the true optimal value that maximizes the cognizance rate.

The expression for the cognizance rate given in (10) is not so tractable as to find an optimal value in a closed form. From (14), however, we can easily find a nearly optimal value, which is given in the following theorem.

Theorem 4. Given number of opportunities $K \in \mathbb{N}$, the upper bound $\bar{\rho}_R$ is maximized by a value for the probability of seizing an opportunity, denoted by p^+, such that

$$p^+ = \begin{cases} B[1-(1-\frac{1}{M})^{\frac{1}{K}}] & \text{if} \quad M > \dfrac{1}{1-(1-\frac{1}{B})^K} \\ 1 & \text{if} \quad M \le \dfrac{1}{1-(1-\frac{1}{B})^K}. \end{cases} \tag{15}$$

Also, the maximum value of the upper bound

$$\bar{\rho}_R|_{p=p^+} = \begin{cases} \dfrac{B}{A+B}(1-\frac{1}{M})^{M-1} & \text{if} \quad p^+ \in [0,1) \\ \dfrac{MB}{A+B}(1-\frac{1}{B})^{K(M-1)}[1-(1-\frac{1}{B})^K] & \text{if} \quad p^+ = 1 \end{cases} \tag{16}$$

for all $K \in \mathbb{N}$.

A proof of the theorem is given in the appendix.

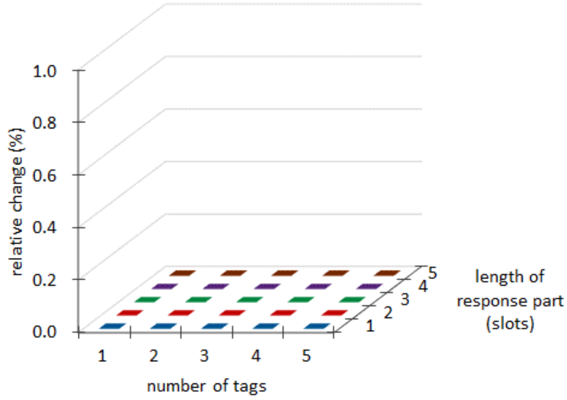
5. Numerical Examples

Using the formulae given by the theorems 1 to 4, we present numerical examples which shows how precise the nearly optimal value for the probability of seizing an opportunity is and whether the randomized scheme is able to dominate the conventional scheme in cognizance rate or not.

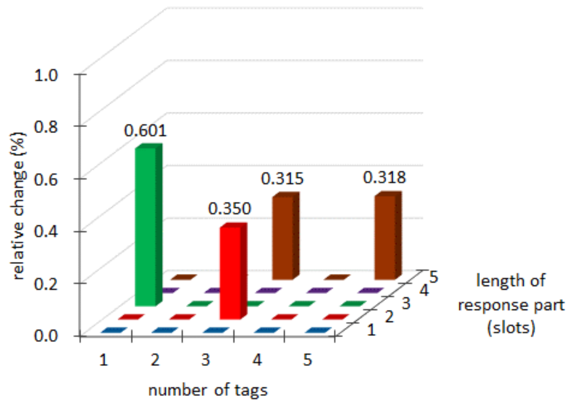
To measure the precision of the nearly optimal value, we introduce the relative change of the cognizance rate, which is defined by

$$r(p^+, p^*) = \frac{\rho_R|_{p=p^*} - \rho_R|_{p=p^+}}{\rho_R|_{p=p^*}} \times 100 \tag{17}$$

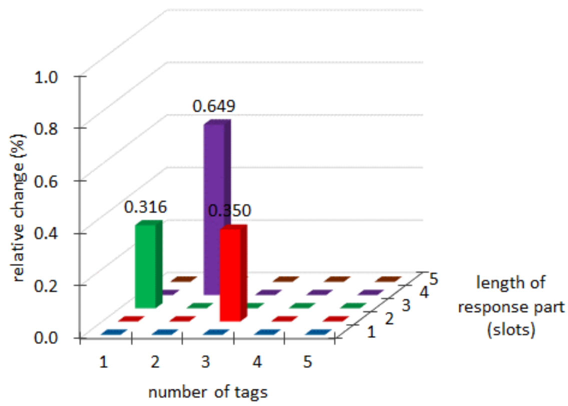
where p^* is an optimal value for the probability of seizing an opportunity which maximizes the cognizance rate while p^+ is a nearly optimal value which maximizes the upper bound on the cognizance rate. Obviously, a small value of the relative change indicates a high precision of the nearly optimal value. **Fig. 8** shows the relative change over the space made of three parameters; number of tags, length of response part and number of opportunities. In this figure, the inquiry part is set to be made of a single slot. In **Fig. 8**, we observe that the relative change remains below 0.7% in any case. Such an observation strongly implies that the nearly optimal value is highly precise.



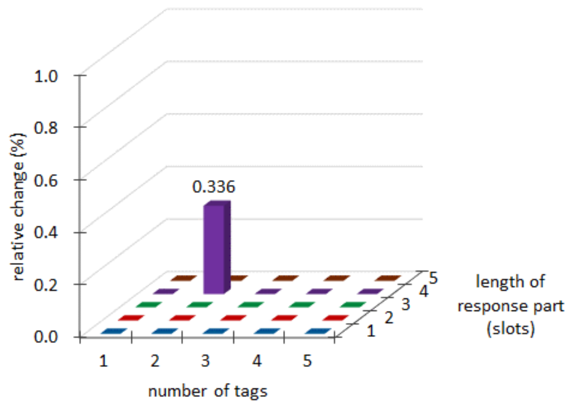
(a) Number of opportunities $K = 1$.



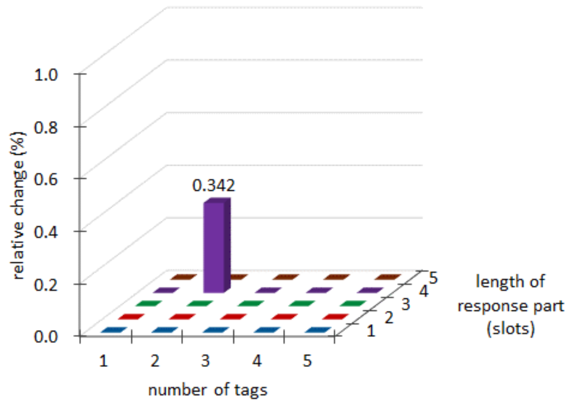
(b) Number of opportunities $K = 2$.



(c) Number of opportunities $K = 3$.



(d) Number of opportunities $K = 4$.



(e) Number of opportunities $K = 5$.

Fig. 8. Relative change vs. number of tags and length of response part.

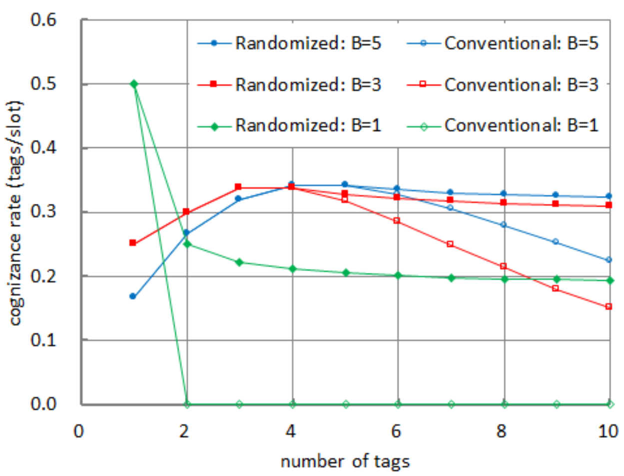


Fig. 9. Cognizance rate vs. number of tags.

Fig. 9 shows the cognizance rate attained by the randomized scheme. In this figure, the inquiry part is made of a single slot and the number of opportunities is fixed to 1. Also, it is assumed that the reader exactly knows the number of neighboring tags and employs the nearly optimal value for the probability of seizing an opportunity. In **Fig. 9**, we observe that the randomized scheme is able to dominate the conventional scheme in cognizance rate over a wide range of the number of tags.

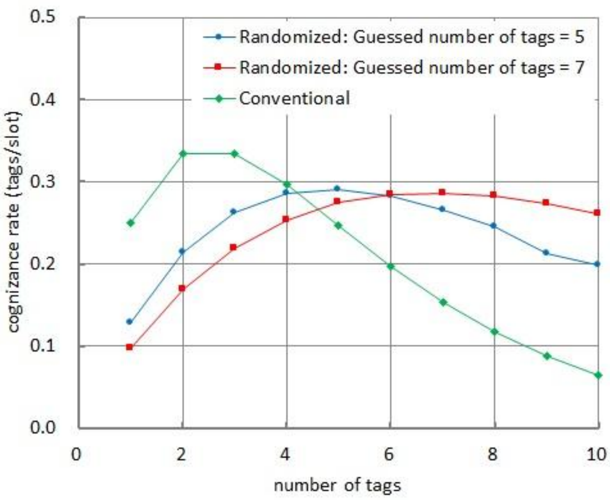


Fig. 10. Cognizance rate vs. number of tags.

In an RFID network, a reader may have either wrong information or no information about the number of neighboring tags. In such a situation, the reader may either believe in a wrong number of tags or guess a wrong number. **Fig. 10** considers such a situation and shows the impact of believing or guessing a wrong number of tags. In this figure, the inquiry and response parts are made of 1 and 3 slots, respectively. Also, the number of opportunities is fixed to 3. In **Fig. 10**, we observe that the randomized scheme exhibits a better cognizance rate than the conventional scheme as far as the number that the reader believes or guesses is not significantly smaller than the true number of tags.

6. Conclusion

In this paper, we considered an RFID network which consists of a single reader and many tags. Such a network needs a tag cognizance scheme, which is able to arbitrate among the tags contending to respond. Bearing in mind inexpensive applications, which support a relatively small number of tags, we confined our attention to the clan of unrestricted and static schemes. Then, aiming at enhancing tag cognizance rate as well as not losing simplicity than a conventional scheme, we proposed a randomized scheme for cognizing tags. To evaluate the proposed scheme, we then derived an exact expression for the cognizance rate attained by the randomized scheme. The cognizance rate can be maximized by employing an optimal value for the probability of making a selection. Unfortunately, the exact expression is not so tractable as to find an optimal value in an analytical fashion. As an alternative way, we thus developed a tight upper bound on the cognizance rate and presented an exact expression for the upper bound. In a closed form, we then obtained a nearly optimal value (for the probability of seizing an opportunity) which maximizes the upper bound. Numerical examples showed that the relative change of cognizance rate is extremely low and the nearly optimal value is thus highly precise. Also, numerical examples confirmed that the randomized scheme is able to dominate the conventional scheme in cognizance rate by employing the nearly optimal value. Furthermore, numerical examples revealed that the randomized scheme is robust to the fallacy that the reader believes or guesses a wrong number of neighboring tags.

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Appendix

A.1 Proof of theorem 1

Let Z_{bn} denote the number of tags that the reader cognizes in the bth slot of the nth frame for $b \in \{1, \cdots, B\}$ and $n \in \{1, 2, \cdots\}$. Then, the number of tags that the reader cognizes during the nth frame is represented by

$$X_n = \sum_{b=1}^{B} Z_{bn} \tag{A1}$$

for $n \in \{1, 2, \cdots\}$. Also, the expected number of such tags

$$E(X_n) = BP(Z_{bn} = 1) \tag{A2}$$

since $Z_{1n}, \cdots, Z_{Bn}$ are identically distributed by symmetry. Note that $\{Z_{bn} = 1\}$ is equivalent to the event that only one of the M tags responds in the bth slot. Thus, we have

$$P(Z_{bn} = 1) = \binom{M}{1} \frac{1}{B} (1 - \frac{1}{B})^{M-1}. \tag{A3}$$

Therefore, the cognizance rate achieved by the conventional scheme

$$\rho_C = \frac{E(X_n)}{A+B} = \frac{BP(Z_{bn} = 1)}{A+B} = \frac{M}{A+B} (1 - \frac{1}{B})^{M-1}. \tag{A4}$$

A.2 Proof of theorem 2

Recall that S_{mn} denotes the number of slots in which the tag τ_m responds while R_{mn} represents the number of tags that the reader cognizes during the nth frame. Then,

$$P(R_{mn} \geq 1) = \sum_{s=1}^{\min\{K,B\}} P(R_{mn} \geq 1 | S_{mn} = s) P(S_{mn} = s). \tag{A5}$$

First, let T_{mn} denote the number of opportunities at which the tag τ_m makes a selection during the nth frame. Then, T_{mn} has the binomial distribution with parameters K and p, i.e.,

$$P(T_{mn} = t) = \binom{K}{t} p^t (1-p)^{K-t} \tag{A6}$$

for $t \in \{0, \cdots, K\}$ since a tag independently seizes an opportunity with probability p. Also, we have

$$P(S_{mn} = s) = \sum_{t=s}^{K} P(S_{mn} = s | T_{mn} = t) P(T_{mn} = t) \tag{A7}$$

where the conditional event $\{S_{mn} = s\}$ given $\{T_{mn} = t\}$ is equivalent to the event that $B - s$ boxes are empty when t balls are put into B boxes in the classical occupancy problem [35]. Thus,

$$P(S_{mn} = s | T_{mn} = t) = \binom{B}{s} \sum_{d=0}^{s} (-1)^d \binom{s}{d} (\frac{s-d}{B})^t. \quad \text{(A8)}$$

From (A6) and (A8), we have

$$P(S_{mn} = s) = \binom{B}{s} \sum_{d=0}^{s} (-1)^d \binom{s}{d} \sum_{t=s}^{K} \binom{K}{t} p(\frac{s-d}{B})^t (1-p)^{K-t}. \quad \text{(A9)}$$

Secondly, suppose that the tag τ_m responds in s slots, denoted by $\sigma_{\pi_1}, \cdots, \sigma_{\pi_s}$ for $(\pi_1, \cdots, \pi_s) \in \{1, \cdots, B\}^s$ such that $1 \le \pi_1 < \cdots < \pi_s \le B$. Set A_d denote the event that no other tag (except the tag τ_m) responds in the slot σ_{π_d} for $d \in \{1, \cdots, s\}$. Then,

$$P(R_{mn} \ge 1 | S_{mn} = s) = P(A_1 \cup \cdots \cup A_s). \quad \text{(A10)}$$

Let q_c denote the probability that the intersection of any c of $A_1, \cdots, A_s$ takes place, i.e.,

$$q_c = P(A_{\nu_1} \cap \cdots \cap A_{\nu_c}) \quad \text{(A11)}$$

for $(\nu_1, \cdots, \nu_c) \in \{1, \cdots, s\}^c$ such that $1 \le \nu_1 < \cdots < \nu_c \le s$. Then,

$$P(A_1 \cup \cdots \cup A_s) = \sum_{c=1}^{s} \binom{s}{c} (-1)^{c+1} q_c \quad \text{(A12)}$$

by symmetry. Note that

$$q_c = [\sum_{l=0}^{K} \binom{K}{l} p^l (1-p)^{K-l} (\frac{c}{B})^0 (1 - \frac{c}{B})^l]^{M-1} = (1 - \frac{pc}{B})^{K(M-1)}. \quad \text{(A13)}$$

From (A10), (A12) and (A13), we thus have

$$P(R_{mn} \ge 1 | S_{mn} = s) = \sum_{c=1}^{s} \binom{s}{c} (-1)^{c+1} (1 - p\frac{c}{B})^{K(M-1)}. \quad \text{(A14)}$$

Therefore, from (A9) and (A14), we obtain an exact expression for the cognizance rate attained by the randomized scheme in (10).

A.3 Proof of theorem 3

Recall that Z_{bn} denote the number of tags that the reader cognizes in the bth slot of the nth frame. Then, the number of slots in which the reader cognizes a tag

$$Y_n = Z_{1n} + \cdots + Z_{Bn} \tag{A15}$$

for $n \in \{1, 2, \cdots\}$. Note that

$$E(Y_n) = BP(Z_{bn} = 1) \tag{A16}$$

since $Z_{1n}, \cdots, Z_{Bn}$ are identically distributed by symmetry. Let H_{mbn} indicate whether the reader cognizes the tag τ_m or not in the bth slot of the nth frame, i.e.,

$$H_{mbn} = \begin{cases} 1 & \text{if the reader cognizes the tag } \tau_m \text{ in the } b\text{th slot of the } n\text{th frame} \\ 0 & \text{otherwise.} \end{cases} \tag{A17}$$

Then,

$$Z_{bn} = H_{1bn} + \cdots + H_{Mbn} \tag{A18}$$

for $b \in \{1, \cdots, B\}$ and $n \in \{1, 2, \cdots\}$. Since $H_{1bn}, \cdots, H_{Mbn}$ are identically distributed by symmetry, we have

$$E(Z_{bn}) = MP(H_{mbn} = 1). \tag{A19}$$

Note that $\{H_{mbn} = 1\}$ is the event that only the tag τ_m responds in the bth slot of the nth frame. Thus,

$$P(H_{mbn} = 1) = [(1 - \frac{1}{B})^K]^{M-1}[1 - (1 - \frac{1}{B})^K]. \tag{A20}$$

Therefore, we have

$$\bar{\rho}_R = \frac{E(Y_n)}{A + B} = \frac{MB}{A + B}(1 - \frac{1}{B})^{K(M-1)}[1 - (1 - \frac{1}{B})^K]. \tag{A21}$$

A.4 Proof of theorem 4

Note that the upper bound $\bar{\rho}_R$ is a differentiable function of p. By differentiating $\bar{\rho}_R$ with respect to p, we find a critical point of $\bar{\rho}_R$, denoted by $\tilde{p}$, as follows:

$$\tilde{p} = B[1 - (1 - \frac{1}{M})^{\frac{1}{K}}]. \tag{A22}$$

The upper bound $\bar{\rho}_R$ is a monotone increasing function of $p \in [0, \tilde{p})$while it is monotone decreasing in $p \in (\tilde{p}, \infty)$. Thus, $\tilde{p}$ is a maximum point. Also, note that

$$\begin{aligned} &\tilde{p} \in [0,1) \quad \text{if} \quad M > \frac{1}{1-(1-\frac{1}{B})^K} \\ &\tilde{p} \in [1,\infty) \quad \text{if} \quad M \le \frac{1}{1-(1-\frac{1}{B})^K}. \end{aligned} \tag{A23}$$

Therefore, the upper bound on the cognizance rate $\bar{\rho}_R$ is maximized by a value of p, denoted by p^+, such that

$$p^+ = \begin{cases} B[1-(1-\frac{1}{M})^{\frac{1}{K}}] & \text{if} \quad M > \frac{1}{1-(1-\frac{1}{B})^K} \\ 1 & \text{if} \quad M \le \frac{1}{1-(1-\frac{1}{B})^K}. \end{cases} \tag{A24}$$

Substituting p^+ for p in (A21), we have the maximum cognizance rate that the randomized scheme can attain as follows.

$$\bar{\rho}_R|_{p=p^+} = \begin{cases} \frac{B}{A+B}(1-\frac{1}{M})^{M-1} & \text{if} \quad p^+ \in [0,1) \\ \frac{MB}{A+B}(1-\frac{1}{B})^{K(M-1)}[1-(1-\frac{1}{B})^K] & \text{if} \quad p^+ = 1 \end{cases} \tag{A25}$$

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