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# RFID 망에서 프레임화 및 슬롯화된 ALOHA에 기반한 Tag 인식 방식을 위한 최적 시간 구조

# ( Optimal Time Structure for Tag Cognizance Scheme based on Framed and Slotted ALOHA in RFID Networks )

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## 요 약

하나의 reader가 tag의 군집에 둘러싸여 있는 별 형태의 RFID 망을 고려한다. 이러한 RFID 망에서 reader는 tag에 저장된 정보를 얻기 전에 tag의 응답 간 충돌을 중재하면서 tag를 인식하여야 한다. 이러한 목적으로 tag가 응답하도록 프레임마다 정적으로 일정 수의 슬롯을 마련해 주는 프레임화 및 슬롯화된 ALOHA에 기반한 tag 인식 방식을 제안한다. 제안 방식의 인식 성능을 평가하기 위해 주요 성능 척도로 인식 완료 확률과 기대 인식 완료 시간을 선정한다. 이어서 이러한 성능 척도를 계량적으로 계산할 수 있는 방법을 제안한다. 특히 tag가 많지 않은 경우 성능 척도를 closed form으로 도출한다. 다음 인식 시간에 대한 제약 하에서 인식 완료 확률을 최대화하거나 기대 인식 완료 시간을 최소화하는 최적의 시간 구조를 찾는 문제를 구성한다. 마지막으로 이러한 문제를 풀어서 프레임 당 tag가 응답하기 위한 슬롯의 최적 수를 구한다. 계량적 결과로부터 tag가 응답하기 위한 슬롯의 유한한 최적 수가 존재함을 확인한다. 또한 인식 완료 확률을 최대화하는 최적 슬롯 수는 인식 시간에 대한 제약이 약해지면서 기대 인식 완료 시간을 최소화하는 최적의 슬롯 수로 접근하는 경향을 보임을 관찰한다.

## Abstract

Consider an RFID network configured as a star such that a single reader is surrounded by a crowd of tags. In the RFID network, prior to attaining the information stored at a tag, the reader must cognize the tags while arbitrating a collision among tags' responses. For this purpose, we present a tag cognizance scheme based on framed and slotted ALOHA, which statically provides a number of slots in each frame for the tags to respond. For the evaluation of the cognizance performance, we choose the cognizance completion probability and the expected cognizance completion time as key performance measures. Then, we present a method to numerically calculate the performance measures. Especially, for small numbers of tags, we derive them in a closed form. Next, we formulate a problem to find an optimal time structure which either maximizes the cognizance completion probability under a constraint on the cognizance time or minimizes the expected cognizance completion time. By solving the problem, we finally obtain an optimal number of slots per frame for the tags to respond. From numerical results, we confirm that there exist a finite optimal number of slots for the tags to respond. Also, we observe that the optimal number of slots maximizing the cognizance completion probability tends to approach to the optimal number of slots minimizing the expected cognizance completion time as the constraint on the cognizance time becomes loose.

**Keywords:** RFID network; tag cognizance; framed and slotted ALOHA; cognizance completion; optimal structure

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## Ⅰ. Introduction

Radio frequency identification (RFID) is a system where a reader, in a contactless fashion, attains the information stored at an electronic tag by using a radio wave[1~2]. In this paper, we consider an RFID network configured as a star such that a single reader is located in the middle of the crowd of tags. In an RFID network, a reader hardly knows about the tags in its vicinity. Thus, the reader must cognize the neighboring tags prior to attaining the information stored at a tag. To cognize a tag, the reader usually broadcasts the inquiry about the identities of tags and each tag makes response to the inquiry. In an RFID network configured as a star, two or more tags may attempt to respond at the same time, which results in a collision among the tags' responses. For arbitrating a collision which takes place in the tag cognizance process, tag cognizance schemes based on framed and slotted ALOHA and binary tree schemes were proposed and adopted in some standards[1~2]. In a tag cognizance scheme based on framed and slotted ALOHA, time is divided into frames and a number of slots are provided in each frame. Then, each tag randomly selects a slot in the frame and attempts to respond using the selected slot. In the scheme, the number of slots provided in a frame highly affects the tag cognizance performance. Naturally, efforts were made to determine the number of slots in an optimal fashion. Most of previous works, however, focused on a dynamic design of the number of slots so as to maximize the cognizance rate, for example[3~8].

In this paper, we present a tag cognizance scheme based on framed and slotted ALOHA which statically provides a fixed number of slots in each frame. Since the tag cognizance must precede the main process of attaining the information stored at a tag, it is obviously desirable to reduce the time for the reader to cognize the tags. As performance measures, we thus choose the cognizance completion probability (defined as the probability that the reader cognizes all the tags lying in its vicinity) and the expected cognizance completion time (defined as the expected value of the time elapsed until the reader cognizes all the neighboring tags). As frames go by, the number of tags that the reader has cognized shows the Markov property as will be explained in section 3. Using the property, we then present a method to numerically calculate he cognizance completion probability and the distribution for the cognizance completion time. Especially, for small numbers of tags, we explicitly derive them in a closed form. Next, we formulate a problem to find an optimal time structure which maximizes either the cognizance completion probability under a constraint on the cognizance time or the expected cognizance completion time. Solving the problem, we obtain an optimal number of slots provided in each frame for the tags to respond.

In section Ⅱ, we present a tag cognizance scheme based on static framed and slotted ALOHA. In section Ⅲ, we calculate the cognizance completion probability and the distribution for the cognizance completion time. In section Ⅳ, we formulate a problem to find an optimal time structure for cognizing tags and obtain an optimal number of slots provided in each frame for tags' responses by solving the problem.

## Ⅱ. Tag Cognizance Scheme

In this section, we present a tag cognizance scheme based on static framed and slotted ALOHA. In the scheme, time is divided into frames and a frame is again divided into the inquiry and response parts. Each part also consists of a number of slots which have the same length. Figure 1 shows an exemplary time structure employed in the proposed scheme, where the inquiry part of each frame consists of 1 slot while the response part is comprised of 3 slots in a static fashion.

In each frame, the reader inquires the identity of a tag by using the inquiry part of the frame. Upon the

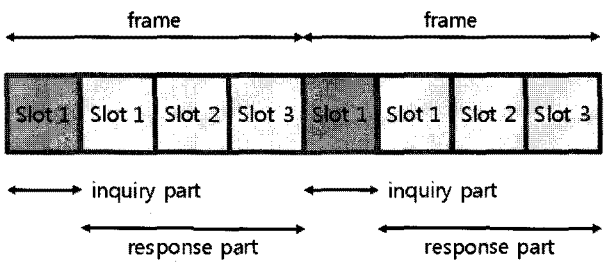


그림 1. 제안하는 tag 인식 방식에 도입된 시간 구조의 예

Fig. 1. Exemplary time structure employed in the proposed tag cognizance scheme.

inquiry, each tag independently and equally likely selects a slot among the slots involving in the response part of the frame. Then, the tag responds to the reader's inquiry using the selected slot.

The proposed tag cognizance scheme is assumed to be used in the following environment. First, as long as the reader proceeds to cognize the tags, no change occurs in the group of the tags. Secondly, two or more tags may select a same slot in the response part of a frame, which results in a collision among the responses of the tags. then, the reader cognizes none of them. Thirdly, a response of a tag may be interfered by the noise in practice. However, we assume a noiseless channel between the MAC entities of the reader and tag.

## Ⅲ. Cognizance Completion Time

In this section, we consider the tag cognizance scheme presented in section 2. The tag cognizance scheme employs the time structure illustrated in figure 1, where the inquiry part of each frame consists of $y$ slots while the response part is comprised of $x$ slots.

Suppose that $M$ tags sojourn in the vicinity of the reader. Let $R_k$ denote the number of tags that the reader cognizes, (i.e., the number of tags which succeed in responding without collision) by the end of the $k$th frame for $k \in \{1,2,\cdots\}$. Then, $R_k$ has the same distribution as the number of boxes with only one ball when $M$ indistinguishable balls are equally likely put into $x$ boxes[9]. Also, the random variables $R_1, R_2, \cdots$ are mutually independent and identically distributed since the number of tags is never changed and the length of a response part is fixed in a static fashion. Let $f$ denote the mass for $R_k$. Then,

$$f(r) = \frac{(-1)^r r! M!}{r! x^M} \times \sum_{j=r}^{\min\{x,M\}} \frac{(-1)^j (x-j)^{M-j}}{(j-r)!(x-j)!(M-j)!} \tag{1}$$

for $r \in \{0,\cdots,\min\{x,M\}\}$.

Note that the reader may have already cognized some of the $R_k$ tags during previous frames. For $k \in \{1,2,\cdots\}$, let $U_k$ denote the number of tags that the reader newly cognizes, (i.e., the number of tags which for the first time succeed in responding) during the $k$th frame. Set

$$V_k = \sum_{j=1}^{k} U_j \tag{2}$$

for $k \in \{1,2,\cdots\}$. Then $V_k$ represents the number of tags that the reader cognizes by the end of the $k$th frame. Since every tag independently attempts to respond in each frame, the sequence $\{V_k, k=0,1,\cdots\}$ is a Markov chain on the finite state space $S=\{0,\cdots,M\}$. (We set $V_0 = 0$ almost surely.) Note that the lengths of inquiry and response parts of each frame are fixed to $y$ and $x$ slots, respectively, in a static fashion. Thus, the Markov chain $\{V_k, k=0,1,\cdots\}$ is also homogeneous. Let $g : S^2 \rightarrow [0,1]$ be the stationary transition probability function of the homogeneous Markov chain $\{V_k, k=0,1,\cdots\}$. Then,

$$\begin{aligned} & g(p,q) \\ & = P(V_{k+1} = q \mid V_k = p) \\ & = \sum_{r=q-p}^{q} P(U_{k+1} = q-p \mid V_k = p, R_{k+1} = r) \\ & \quad \cdot P(R_{k+1} = r) \end{aligned} \tag{3}$$

for $p \in S$ and $q \in \{p,\cdots,M\}$. Given $V_k$ and $R_{k+1}$,

$U_{k+1}$ has a hypergeometric distribution since every tag independently and equally likely chooses a slot in the response part of each frame. Thus, we have

$$g(p,q) = \sum_{r=q-p}^{q} \frac{\binom{M-p}{q-p}\binom{p}{r-q+p}}{\binom{M}{r}} f(r) \quad (4)$$

for $p \in S$ and $q \in \{p,\cdots,M\}$. Note that the Markov chain $\{V_k, k=0,1,\cdots\}$ is a non-decreasing sequence and the state $\{M\}$ is an absorbing state.

For $n \in \{1,2,\cdots\}$, let $h_n$ denote the mass for $V_n$, i.e.,

$$h_n(q) = P(V_n = q) \quad (5)$$

for $q \in S$. Note that the mass is calculated by use of the transition probability function as follows:

$$h_n(q) = \sum_{p_1 \in S} \cdots \sum_{p_{n-1} \in S} g(0,p_1) \cdots g(p_{n-1},q) \quad (6)$$

for $q \in S$ and $n \in \{1,2,\cdots\}$.

Recall that the cognizance completion probability is the probability that the reader cognizes all the tags in its vicinity. Let $\phi_n(x)$ denote the cognizance completion probability by the $n$th frame when the response part of each frame consists of $x$ slots. Then, we have

$$\begin{aligned}\phi_n(x) &= h_n(M) \\ &= \sum_{p_1 \in S} \cdots \sum_{p_{n-1} \in S} g(0,p_1) \cdots g(p_{n-1},M)\end{aligned} \quad (7)$$

for $n \in \{1,2,\cdots\}$ and $x \in \{1,2,\cdots\}$. In general, a large amount of computation is needed to obtain the cognizance completion probability. For small numbers of tags, the following theorem shows the cognizance completion probability in a tractable form.

Lemma: For the number of tags $M \in \{1,\cdots,5\}$, let $\omega_q$ denote the value of the transition probability function $g(q,q)$ for $q \in \{0,\cdots,M-1\}$. Then,

$$\omega_0 = \begin{cases} 0 & \text{for } M=1 \\ \frac{x}{x^2} & \text{for } M=2 \\ \frac{x}{x^3} & \text{for } M=3 \\ \frac{x(3x-2)}{x^4} & \text{for } M=4 \\ \frac{x(10x-9)}{x^5} & \text{for } M=5 \end{cases}$$

$$\omega_1 = \begin{cases} \frac{x}{x^2} & \text{for } M=2 \\ \frac{x^2}{x^3} & \text{for } M=3 \\ \frac{x(4x-3)}{x^4} & \text{for } M=4 \\ \frac{x(3x^2+2x-4)}{x^5} & \text{for } M=5 \end{cases}$$

$$\omega_2 = \begin{cases} \frac{x(2x-1)}{x^3} & \text{for } M=3 \\ \frac{x(x^2+2x-2)}{x^4} & \text{for } M=4 \\ \frac{x(7x^2-9x+3)}{x^5} & \text{for } M=5 \end{cases}$$

$$\omega_3 = \begin{cases} \frac{x(3x^2-3x+1)}{x^4} & \text{for } M=4 \\ \frac{x(x^3+6x^2-12x+6)}{x^5} & \text{for } M=5 \end{cases}$$

$$\omega_4 = \frac{x(4x^3-6x^2+4x-1)}{x^5} \quad \text{for } M=5. \quad (8)$$

Proof: A straightforward calculation from (1) and (3) yields the values of the transition probability function in (8).

**Theorem 1**: For the number of tags $M \in \{1,\cdots,5\}$, the cognizance completion probability $\phi_n(x)$ is expressed as follows:

$$\phi_n(x) = \begin{cases} 1 & \text{for } M=1 \\ 1-\omega_0^n & \text{for } M=2 \\ 1-3\omega_2^n+3\omega_1^n-\omega_0^n & \text{for } M=3 \\ 1-4\omega_3^n+6\omega_2^n-4\omega_1^n+\omega_0^n & \text{for } M=4 \\ 1-5\omega_4^n+10\omega_3^n-10\omega_2^n+5\omega_1^n-\omega_0^n & \text{for } M=5 \end{cases} \quad (9)$$

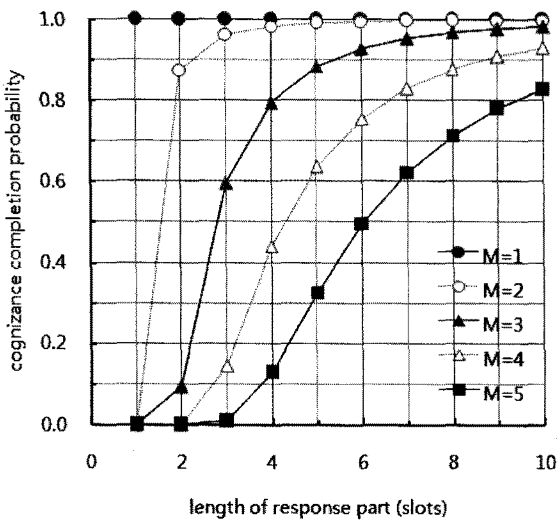


그림 2. 응답부의 길이에 따른 인식 완료 확률
Fig. 2. Cognizance completion probability with respect to length of response part.

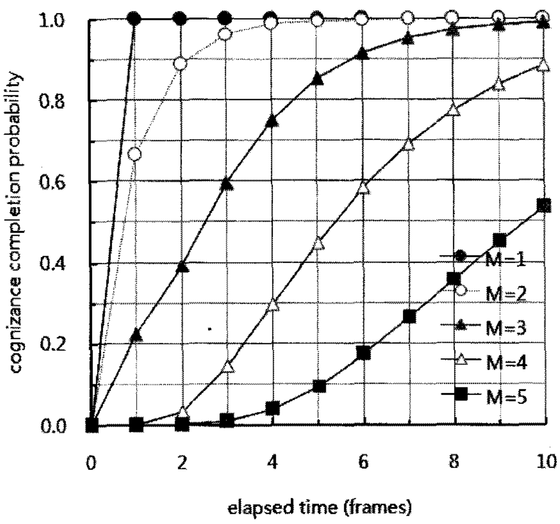


그림 3. Tag 인식에 사용된 시간에 따른 인식 완료 확률
Fig. 3. Cognizance completion probability with respect to time elapsed for cognizing tags.

where $\omega_0,\cdots,\omega_4$ are given in (8).

Proof: A straightforward calculation from (7) yields the cognizance completion probability $\phi_n(x)$ in (9).

Figure 2 shows the cognizance completion probability until the 3rd frame with respect to the length of the response part. In this figure, the length of inquiry part is set to be 1 slot. As expected, it is observed that the cognizance completion probability decreases as the number of tags increases for given length of the response part. Also observed is that the cognizance completion probability increases as the length of response part increases for given number of tags, which is obvious since more time is allowed for the reader to cognize the tags as the length of the response part increases.

Figure 3 shows the cognizance completion probability with respect to the time elapsed for the reader to cognize the tags. In this figure, the length of the inquiry part is set to be 1 slot and the length of the response part is fixed to 3 slots. As observed in figure 2, it is also observed in figure 3 that the cognizance completion probability decreases as the number of tags increases at the end of any frame. As more time elapses for the reader to cognize the tags, it is noticed that the cognizance completion probability increases and tends to converge to 1.

Recall that the cognizance completion time is the time elapsed until the reader cognizes all the tags lying in its vicinity. Let $C$ denote the cognizance completion time measured in slots. Then,

$$C=\min\{n\in\{1,2,\cdots\}: V_n=M\}\cdot(y+x) \quad (10)$$

where $y$ and $x$ are the lengths of inquiry and response parts, respectively. Noting that $h_n$ is the mass for $V_n$,

$$h_n(M)=P(\frac{C}{y+x}\in\{1,\cdots,n\}) \quad (11)$$

for $n\in\{1,2,\cdots\}$. Thus, we have the mass for $C$ as follows:

$$P(C=n(y+x))=h_n(M)-h_{n-1}(M) \quad (12)$$

for $n\in\{1,2,\cdots\}$, where $h_0$ is a function on $S$ such that $h_0(q)=I_{\{q=0\}}$. From (9), we can easily calculate the mass for the cognizance completion time $C$ for the number of tags $M\in\{1,\cdots,5\}$.

Theorem 2: For the number of tags $M\in\{1,\cdots,5\}$, the expected cognizance completion time $E(C)$ is calculated as follows:

$$E(C) = \begin{cases} y+x & \text{for } M=1 \\ \dfrac{y+x}{1-\omega_0} & \text{for } M=2 \\ \dfrac{3(y+x)}{1-\omega_2} - \dfrac{3(y+x)}{1-\omega_1} + \dfrac{y+x}{1-\omega_0} & \text{for } M=3 \\ \dfrac{4(y+x)}{1-\omega_3} - \dfrac{6(y+x)}{1-\omega_2} + \dfrac{4(y+x)}{1-\omega_1} - \dfrac{y+x}{1-\omega_0} & \text{for } M=4 \\ \dfrac{5(y+x)}{1-\omega_4} - \dfrac{10(y+x)}{1-\omega_3} + \dfrac{10(y+x)}{1-\omega_2} - \dfrac{5(y+x)}{1-\omega_1} + \dfrac{y+x}{1-\omega_0} & \text{for } M=5. \end{cases} \quad (13)$$

Proof: From (9) and (12), the cognizance completion time has a weighted, superposed and shifted geometric distribution. Weighting and superposing the expected values of shifted geometric distributions yields (13).

Figure 4 shows the expected cognizance completion time with respect to the length of the response part. In this figure, the length of the inquiry part is set to be 1 slot. In figure 4, it is observed that there exists a finite length of the response part which minimizes the expected cognizance completion time. This phenomenon happens since a short length of the response part frequently incurs a collision among tags' responses while a long length of the response part brings about many slots unused by any tag.

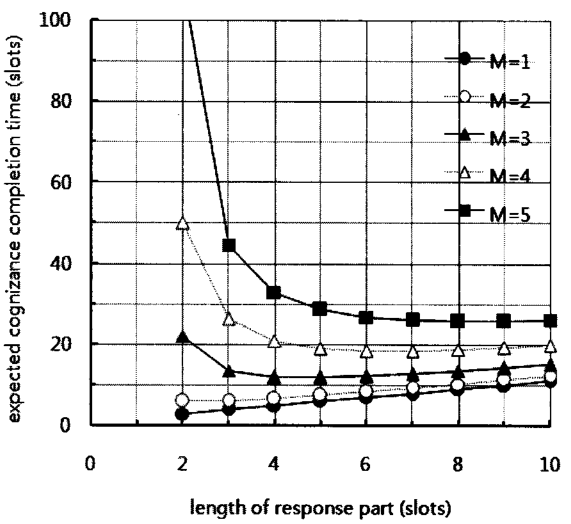


그림 4. 응답부의 길이에 따른 인식 완료 기대 시간
Fig. 4. Expected cognizance completion time with respect to length of response part.

## IV. Optimal Time Structure

In this section, we construct an optimal time structure for the proposed tag cognizance scheme. The optimality is defined in two ways. First, a time structure is said to be optimal if it maximizes the cognizance completion probability under a constraint on the cognizance time. Secondly, a time structure is also said to be optimal if it minimizes the expected cognizance completion time.

A problem to find an optimal time structure in the first sense is formulated as follows:

Given $M$ and $y$
maximize $\phi_n(x)$
with respect to $n \in \{1,2,\cdots\}$ and $x \in \{1,2,\cdots\}$
subject to $n(y+x) \le \gamma$ (14)

where $\gamma \in \{2,3,\cdots\}$ is the constraint on the cognizance time. Let $x^*$ and $n^*$ denote the optimal length of the response part and the corresponding optimal number of frames in which the reader cognizes the tags. Note that the cognizance completion probability is maximized when the cognizance time is fully utilized. Thus,

$$n^* = \left\lceil \frac{\gamma}{y+x^*} \right\rceil . \quad (15)$$

Figure 5 shows the cognizance completion probability with respect to the length of the response part. In this figure, 5 tags are assumed to sojourn in the vicinity of the reader ($M=5$) and the length of the inquiry part is set to be 1 slot ($y=1$). In figure 5, it is observed that there exists a finite length of the response part which maximizes the cognizance

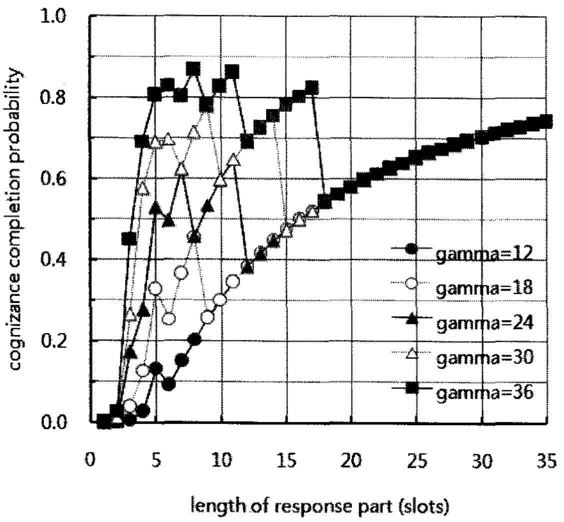


그림 5. 응답부의 길이에 따른 인식 완료 확률

Fig. 5. Cognizance completion probability with respect to length of response part.

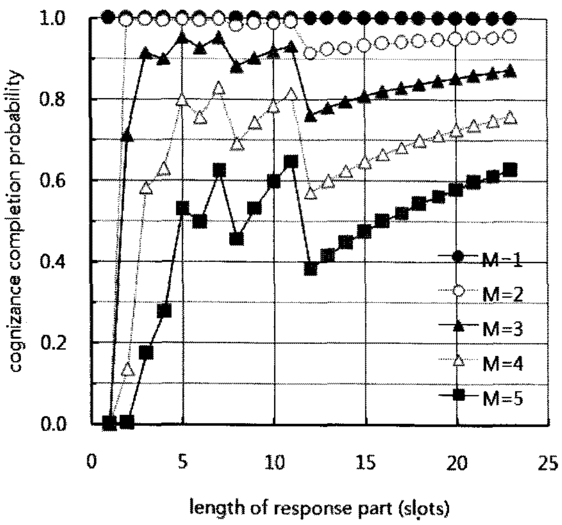


그림 6. 응답부의 길이에 따른 인식 완료 확률

Fig. 6. Cognizance completion probability with respect to length of response part.

completion probability for given constraint on the cognizance time. Also noticed is that the cognizance completion probability is maximized only if the frame length is a factor of the constraint on the cognizance time.

Figure 6 shows the cognizance completion probability with respect to the length of the response part. In this figure, the length of the inquiry part is set to be 1 slot ($y=1$) and the constraint on the cognizance time is fixed to 24 slots. In figure 6, it is observed that there exists a finite length of the response part which maximizes the cognizance completion probability for given number of tags. It is also noticed that a shorter length of the response part maximizes the cognizance completion probability for a larger number of tags.

표 1. 응답부의 최적 길이

Table 1. Optimal length of response part. ($M$: the number of neighboring tags, $\gamma$: constraint on cognizance time)

| Optimal length in the first sense | | | | | |
|---|---|---|---|---|---|
| $M$ / $\gamma$ | 1 | 2 | 3 | 4 | 5 |
| 12 | 1 | 3 | 11 | 11 | 11 |
| 18 | 1 | 5 | 5 | 8 | 17 |
| 24 | 1 | 3 | 5 | 7 | 11 |
| 30 | 1 | 4 | 5 | 9 | 9 |
| 36 | 1 | 3 | 5 | 8 | 8 |
| Optimal length in the second sense | | | | | |
| | 1 | 2 | 5 | 6 | 8 |

A problem to find an optimal time structure in the second sense is formulated as follows:

$$\begin{aligned}&\text{Given } M \text{ and } y\\&\text{maximize } E(C)\\&\text{with respect to } x\in\{1,2,\cdots\}.\end{aligned} \tag{16}$$

For the number of tags $M\in\{1,\cdots,5\}$, figure 4 illustrates the optimal length of the response part when the length of the inquiry part $y$ is equal to 1 slot. Table 1 shows such an optimal length (in the second sense) of the response part in comparison with the optimal length (in the first sense). As the constraint on the cognizance time becomes loose, it is observed that the optimal length in the first sense decreases and tends to approach to the optimal length in the second sense.

## V. Conclusions

In this paper, we considered an RFID network which consists of a reader and a crowd of tags in the vicinity of the reader. In the RFID network, prior to attaining the information stored at a tag, the reader must cognize the tags while arbitrating a collision among tags' responses. For this purpose, we presented a tag cognizance scheme based on framed and slotted ALOHA, which statically provides a number of slots in each frame for the tags to respond. For the evaluation of the cognizance performance, we chose the cognizance completion probability and the expected cognizance completion time as key performance measures. Then, we developed a method to numerically calculate the performance measures. Especially, we derived them in a closed form when the number of tags is small. Next, we formulated a problem to find an optimal time structure which either maximizes the cognizance completion probability under a constraint on the cognizance time or minimizes the expected cognizance completion time. By solving the problem, we finally obtained an optimal number of slots per frame for the tags to respond. From numerical results, we confirmed that there exist a finite optimal length of the response part. Also, we observed that the optimal length of the response part maximizing the cognizance completion probability tends to approach to the optimal length minimizing the expected cognizance completion time as the constraint on the cognizance time becomes loose.

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