# Approximate Analysis of MAC Protocol with Multiple Self-tokens in a Slotted Ring

Makoto Sakuta and Iwao Sasase

*Abstract:* **Ring networks are very commonly exploited among local area and metropolitan area networks (LAN/MAN), whereas cells or small fixed-size packets are widely used in synchronized ring networks. In this paper, we present an analytical method for evaluating the delay-throughput performance of a MAC protocol with multiple self-tokens in a slotted ring network under uniform traffic. In our analysis, we introduce the stationary probability, which indicates the number of packets in a node. Also, it is assumed that each node has a sufficiently large amount of self-tokens, and a slotted ring has the symmetry. The analytical results with respect to delay-throughput performance have similar values to computer simulated ones. Furthermore, in order to achieve fair access under non-uniform traffic, we propose an adaptive MAC protocol, where the number of self-tokens in a node dynamically varies, based on the number of packets transmitted within a specified period. In the proposed protocol, when the number of packets transmitted by a node within a specified period is larger than a specified threshold, the node decreases the number of self-tokens in a per-node distributed method. That results in creating free slots in the ring, thus all nodes can obtain an equal opportunity to transmit into the ring. Performance results obtained by computer simulation show that our proposed protocol can maintain throughput fairness under non-uniform traffic.**

*Index Terms:* **Self-token, slotted ring, throughput, non-uniform traffic, fairness.**

## I. INTRODUCTION

Ring networks are very commonly exploited among local area and metropolitan area networks (LAN/MAN). Those provide several advantages such as reliability in the case of physical damages to the network, ease of slot synchronization at extremely high data rates, and so on [1], [2]. Ring networks are roughly classified into slotted ring and buffer insertion ring(or unslotted ring) networks. In general, slotted networks have the advantage that they have fewer contentions than unslotted networks. Moreover, the widespread use of cells or small fixed-size packets, as well as the synchronization of the network operations such as in SONET/SDH ring lead to a slotted ring model [2], [5], [6]. Therefore, we focus on a slotted ring in this paper.

Token ring protocol is a well-known media access control (MAC) protocol for the ring network. Since at most one node which holds the token can transmit into the ring at any given time, token ring protocol has a problem of throughput degradation in the case of high load. To solve the problem, ring networks with spatial reuse are focused on, in which multiple simultaneous transmissions are allowed as long as they take place over different links [3]. In such networks, total ring throughput becomes much higher than the capacity of a single link. However, the spatial reuse access mechanism leads throughput unfairness among nodes in the case of high load.

In order to ensure a measure of access fairness among nodes connected to the ring network, several quota-based MAC protocols have been proposed [4]–[8]. In those protocols, a node is allowed to transmit a certain amount of packets in a cycle, which is called *quota*. Therefore, each node has the equal opportunity to transmit into the ring. However, those protocols have the disadvantage that the node, which has exhausted its quota, must wait for a next packet transmission until all other nodes exhaust their quotas. Meanwhile, a self-token protocol has been proposed [9], in which a node has an amount of self-tokens for transmitting a packet. Therefore, the transmission by a node does not depend on the amount of self-tokens in other nodes. Also, it has been shown by computer simulations that the amount of self-tokens largely effects to the delay-throughput performance. However, performances of the MAC protocol with multiple self-tokens have not been analyzed in [9]. Hence, it is very important to clarify delay-throughput performance of the MAC protocol with multiple self-tokens for given parameters by an analytical method.

On the other hand, when heavy load nodes continuously hold the transmission channel for a long time, or under non-uniform traffic, throughput unfairness occurs. In such a situation, as the number of self-tokens becomes large, most of the slots become occupied with packets transmitted by some of nodes. Under non-uniform traffic, the number of self-tokens should be dynamically varied in order to achieve throughput fairness. In the adaptive self-token protocol for a buffer insertion ring shown in [10], the amount of self-tokens is dynamically varied based on the duration which it takes for a self-token to round the ring. However, the duration is always same in a slotted ring. Since the throughput unfairness occurs, the protocol [10] is not an effective for a slotted ring. Therefore, we need an efficient MAC protocol, which can achieve fair access to the ring even under non-uniform traffic.

In this paper, we present an analytical method for evaluating the delay-throughput performance of a MAC protocol with multiple self-tokens in a slotted ring under uniform traffic. In our analytical model, we introduce the stationary probability, which indicates the number of packets in a node. For the simplification, it is assumed that a node has a sufficiently amount

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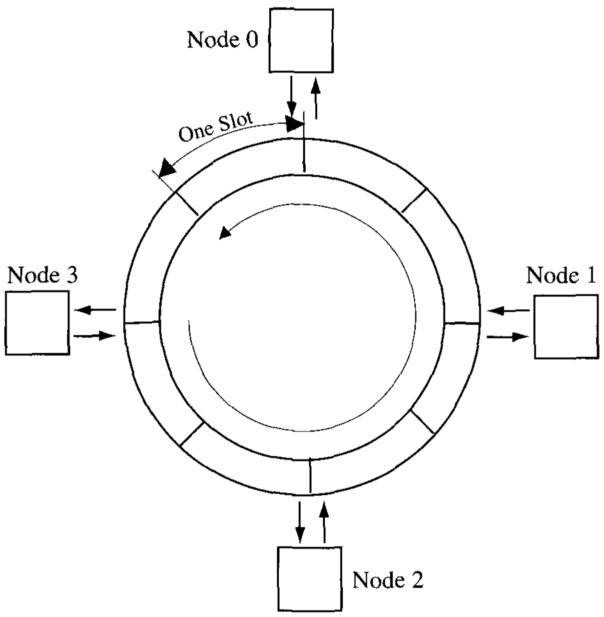


Fig. 1. A slotted ring with four nodes.

of self-tokens, and a slotted ring is symmetric. Under the above conditions, the transition of queue length is modeled by Markov chain, and we can derive the delay-throughput performance for the MAC protocol with multiple self-tokens under uniform traffic. We compare the analytical results with the computer simulated ones with respect to the delay-throughput performance. The analytical results have similar values to computer simulated ones in the case that the number of self-tokens is sufficiently large. Thus, both the propriety of our analytical model and a validation of the computer simulation model are shown.

Furthermore, in order to achieve the fairness of throughput per node under non-uniform traffic in a slotted ring, we propose an adaptive MAC protocol, where the number of self-tokens dynamically varies, based on the number of packets transmitted within a specified period. In the proposed protocol, when the number of packets transmitted by a node within a specified period is larger than a specified threshold, the node decreases the number of self-tokens in a per-node distributed method. That results in creating free slots in the ring, thus all nodes can obtain equal opportunity to transmit into the ring. From computer simulated results with regard to throughput per node, we show that our proposed protocol can achieve the throughput fairness under non-uniform traffic.

In Section II, we address an overview of the MAC protocol with multiple self-tokens [9]. In Section III, we present the analytical model for the MAC protocol in a slotted ring under uniform traffic. Furthermore, in Section IV, we propose the adaptive MAC protocol which can achieve fair access to the ring under non-uniform traffic. Numerical results are presented in Section V. Finally, conclusion remarks are given in the last section.

## II. THE MAC PROTOCOL WITH MULTIPLE SELF-TOKENS IN A SLOTTED RING

One of the purposes of this paper is to provide the analytical method for evaluating delay-throughput performance for the MAC protocol with multiple self-tokens in a slotted ring. In this section, we address an overview of the MAC protocol with multiple self-tokens [9].

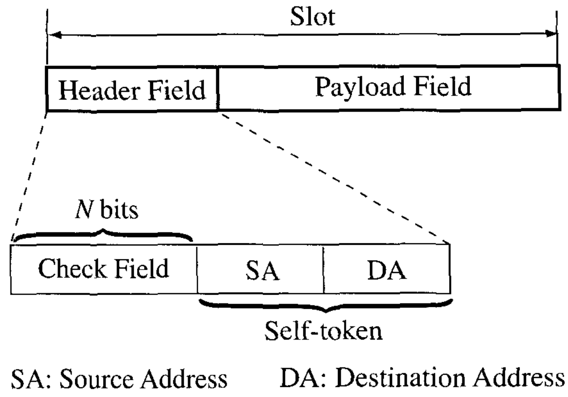


Fig. 2. The structure of a slot.

Fig. 1 shows a slotted ring with four nodes. Time is slotted, and a packet transmitted to the ring moves slot by slot along the ring. It is assumed that all slots are synchronized. There are $S$ slots in the ring, where $S = mN$, for positive integer number $m$. Nodes are equipped with one transmitter and one receiver. They can transmit or receive only one packet within one time slot. Also, the node has $T$ self-tokens initially. Generally, a token is shared among all nodes in the network. The node which has a token is allowed to transmit a packet into the ring. On the other hand, a self-token is a token specific for a node, and a node is allowed to transmit a packet toward the ring if the node has at least one self-token. One self-token is used for transmitting one packet. Each node has two buffers. One is a node buffer for storing the packets generated at the node, and another is a self-token buffer for storing its own self-tokens. The node buffer size is denoted by $B$.

Fig. 2 shows the structure of a slot. A slot consists of a header field and a payload field. Also, the header field is divided into a self-token field and a check field. The self-token field consists of a source address(SA) field and a destination address(DA) field. The check field consists of $N$ bits, and is used for node $i$ to recognize that its self-token comes back to itself. In [9], the packet and the self-token are removed by the destination node from the ring.

We assume that at the beginning of time slot $t$, node $i$ is about to receive slot $s$ from the ring. At most one packet arrives at a node at the beginning of time slot $t$. What node $i$ has to do within one time slot in the MAC protocol with multiple self-tokens are (1) to receive slot $s$ from the ring, and remove the packet from slot $s$ if the packet destines node $i$, (2) to store an arrival packet in its node buffer, and (3) to transmit slot $s$ filled with a packet into the ring if slot $s$ is available and there are one or more packets in its node buffer. Processes (1) and (2) are performed in parallel, and then the process (3) is performed following processes (1) and (2). Details of three processes are addressed below.

At the beginning of time slot $t$, node $i$ receives slot $s$. Node $i$ checks $i$th bit in the check field in slot $s$. Only when node $i$ finds that $i$th bit is set to 1 in the check field, node $i$ generates one self-token and stores it in its self-token buffer. Furthermore, node $i$ sets $i$th bit in the check field to 0. Also, node $i$ checks DA in the self-token field in slot $s$. When DA is equal to $i$, node $i$ removes the packet and the self-token from slot $s$. That is, node $i$ sets the values of SA and DA, and the payload field in slot $s$ to null.

A packet arrives at node $i$ at the beginning of time slot $t$. If there are $B$ packets in its node buffer, the arrival packet is dropped due to buffer overflow. Otherwise, node $i$ stores it in its node buffer. When node $i$ has no packets in the node buffer, node $i$ stores the arrival packet in the head of its node buffer. Therefore, it is possible that the packet arriving at node $i$ at the beginning of time slot $t$ is transmitted toward the ring until the end of time slot $t$.

After above two processes are done, node $i$ tries to transmit the head packet of the node buffer. Node $i$ checks the number of self-tokens in its self-token buffer. If slot $s$ is available and node $i$ has at least one self-token, node $i$ fills slot $s$ with its self-token and a data packet, respectively. Also, node $i$ sets $i$th bit in the check field to 1. Then, node $i$ transmits slot $s$ into the ring.

Thus, in the MAC protocol with multiple self-tokens [9], each node can transmit a packet in the per-node distributed manner. Transmission by a node does not depend on the number of self-tokens in other nodes.

## III. ANALYTICAL MODEL

In [9], performance of the MAC protocol with multiple self-tokens has not been analyzed. When we design a practical network, we need to analyze performance for given parameters such as the number of nodes and the buffer size. Hence, it is very important to clarify delay-throughput performance of the MAC protocol with multiple self-tokens for given parameters by an analytical method. In this section, we present an analytical method for evaluating the delay-throughput performance for the MAC protocol with multiple self-tokens in a slotted ring under uniform traffic.

First, we make the following assumptions.

**Assumptions**

- $(A1)$ The packet arrival process at each node is assumed to be a Bernoulli process with parameter $\lambda$. Here, $\lambda$ is the probability that one packet arrives at a node per slot.
- $(A2)$ Packets arriving at node $i$ have address $j (j \neq i)$ with probability $1/(N-1)$.
- $(A3)$ The slot size and the packet size are the same.
- $(A4)$ $N$ nodes are located equally along the ring.
- $(A5)$ Each node has $S$ self-tokens. In other words, lack of its self-token does not prevent a node to transmit a packet.
- $(A6)$ The packet in a slot received by a node destines is independent of the state of the node [3]. The queue length indicates the number of packets which a node has.

Assumptions $(A2)-(A4)$ are used to be reasonable that in our analytical model, the slotted ring is symmetric. It is assured by the symmetry of the slotted ring that all slots are free with an equal probability and all nodes can transmit into the ring with an equal probability. In the following description, we focus on the operation of node $i$. Those help the simplification of our analytical derivation of the delay-throughput performance of the MAC protocol with multiple self-tokens.

Nodes have their node buffers whose size is $B (\geq 1)$. The number of packets in a node buffer is called queue length. We denote by $\pi_{(b)} (0 \leq b \leq B)$ the stationary probability that node $i$ has $b$ packets in its node buffer. The transition of queue length is modeled by Markov chain, and induced by the event that a packet newly arrives at node $i$, or that the packet is transmitted from the node buffer into the ring. The transition of queue length depends on not only the current queue length but also the past state of slots in the ring. This can be valid because from assumption $(A6)$, it is regarded that the contents of the slot received by node $i$ does not depend on the past behavior of node $i$.

The probability that node $i$ receives a packet from the ring under the condition that the received slot is not free is $p = 2/N$[3](See Appendix for derivation of $p$). In [3], in the case of a single buffer model, $p = 2/N$ is derived from the symmetry of the ring using assumption $(A2)-(A4)$. In this paper, we can use $p = 2/N$ for the multiple buffer size model, since we assume from assumption $(A6)$ that the contents of the slot received by a node is assured to be independent of the queue length at node $i$. We can say that assumption $(A6)$ is valid because of the symmetry of the system by assumptions $(A2)-(A4)$.

We denote by $\beta$ the probability that the received slot is not free. $\gamma_{rec}$ is defined as the probability that node $i$ receives a packet from the ring per slot, and is expressed as

$$\gamma_{rec} = \beta \cdot p. \tag{1}$$

Our focus is moved to what node $i$ has to do within one time slot. In tandem with receiving a slot from the ring, if a packet newly arrives at node $i$, node $i$ stores it in its node buffer. And then, if the slot is available for node $i$ and there is at least one packet in its node buffer, node $i$ inserts a packet into the slot and transmits it toward the ring. As described in Section II, it is possible that the packet arriving at node $i$ at the beginning of time slot $t$ is transmitted into the ring within time slot $t$.

From assumption $(A1)$, at most one packet newly arrives at node $i$. Also, node $i$ can transmit at most one packet towards the ring. On these basis, we provide three transition probabilities to $\pi_{(b)}$.

*i)* Transition probability from $\pi_{(b+1)}$ to $\pi_{(b)}$
When no packets arrive at node $i$ and the slot is available for node $i$, the queue length varies from $b+1$ to $b$. The probability that the slot is available is derived from the sum of the probability that the slot received by node $i$ is free and the probability that node $i$ receives the packet which destines node $i$ under the condition that the slot is not free. So, the transition probability from $\pi_{(b+1)}$ to $\pi_{(b)}$ is given by $(1-\lambda)(1-\beta+\beta p)$.

*ii)* Transition probability from $\pi_{(b)}$ to $\pi_{(b)}$
The queue length at node $i$ does not change. That is, 1) no packets arrive at node $i$ and the slot is not available for node $i$, or 2) one packet newly arrives at node $i$ and the packet in the head of its node buffer is transmitted into the ring. So, the transition probability from $\pi_{(b)}$ to $\pi_{(b)}$ is given by $(1-\lambda)(\beta-\beta p)+\lambda(1-\beta+\beta p)$.

*iii)* Transition probability from $\pi_{(b-1)}$ to $\pi_{(b)}$
When one packet arrives at node $i$ and the slot is not available for node $i$, queue length varies from $b-1$ to $b$. So, the transition probability from $\pi_{(b-1)}$ to $\pi_{(b)}$ is given by $\lambda(\beta-\beta p)$.

From the above transition probabilities, equations of state for $\pi_{(b)}$ are given by (2) and satisfies (3).

$$\pi_{(b)}=\begin{cases}\{(1-\lambda)+\lambda(1-\beta+\beta p)\}\pi_{(b)} \\ \quad +(1-\lambda)(1-\beta+\beta p)\pi_{(b+1)}, & \text{for } b=0 \\ \lambda(\beta-\beta p)\pi_{(b-1)} \\ \quad +\{(1-\lambda)(\beta-\beta p)+\lambda(1-\beta+\beta p)\}\pi_{(b)} \\ \quad +(1-\lambda)(1-\beta+\beta p)\pi_{(b+1)}, & \text{for } 1\le b\le B-1 \\ \lambda(\beta-\beta p)\pi_{(b-1)}+(\beta-\beta p)\pi_{(b)}, & \text{for } b=B\end{cases} \tag{2}$$

$$\sum_{b=0}^{B}\pi_{(b)}=1. \tag{3}$$

In order to derive the probability that node $i$ transmits a packet toward the ring per slot, denoted by $\gamma_{tr}$, we take the following four events into account.

A: The slot which node $i$ is about to receive is occupied with a packet.

B: The slot which node $i$ is about to receive is not free, and a packet in the slot destines node $i$.

C: Node $i$ has at least one packet in its node buffer.

D: One packet newly arrives at node $i$.

We use the notation $P_r(\mathrm{X})$, which means the probability that event X occurs. Since $\pi_{(0)}$ means the probability that no packets exists in node $i$, $P_r(\mathrm{C})=1-\pi_{(0)}$. Also, since packet arrival process at each node is assumed to be a Bernoulli process with parameter $\lambda$, $P_r(\mathrm{D})=\lambda$.

Node $i$ can transmit a packet if the receiving slot is available and there are at least one packet in its node buffer. $\gamma_{tr}$ is given by $\{P_r(\overline{\mathrm{A}})+P_r(\mathrm{B|A})\mathrm{P_r(A)}\}\cdot\{\mathrm{P_r(C)+P_r(D)-P_r(C\cap D)}\}$. $\gamma_{tr}$ is expressed as

$$\begin{aligned}\gamma_{tr} &= \{P_r(\overline{\mathrm{A}})+P_r(\mathrm{B|A})\mathrm{P_r(A)}\} \\ &\quad \cdot\{P_r(\mathrm{C})+\mathrm{P_r(D)-P_r(C\cap D)}\} \\ &= \{(1-\beta)+\beta p\}\{(1-\pi_{(0)})+\lambda-(1-\pi_{(0)})\cdot\lambda\} \\ &= \{(1-\beta)+\beta p\}\{1-\pi_{(0)}(1-\lambda)\}.\end{aligned} \tag{4}$$

When the system is in the stationary state, it is regarded that $\gamma_{tr}$ is equal to $\gamma_{rec}$. From (1) and (4), $\pi_{(0)}$ is calculated as

$$\pi_{(0)}=\frac{1-\beta}{(1-\lambda)(1-\beta+\beta p)}. \tag{5}$$

From (2), (3) and (5), we can obtain $\beta$, whose value is between 0 and 1. Now, we show the reason why the value of $\beta$ is between 0 and 1. First, we can find that using $\pi_{(0)}$, $\pi_{(b)}(1\le b\le B)$ is expressed as the following equation.

$$\pi_{(b)}=\left\{\left(\frac{\lambda}{1-\lambda}\right)\left(\frac{\beta-\beta p}{1-\beta+\beta p}\right)\right\}^{b}\cdot A\cdot\pi_{(0)}, \quad \text{for } 1\le b\le B, \tag{6}$$

where $A$ is a coefficient whose value is $1-\lambda$ if $b=B$, or 1 if $b\ne B$. By substituting (6) for (3), we can obtain the following equation.

$$\pi_{(0)}+\sum_{b=1}^{B}\left\{\left(\frac{\lambda}{1-\lambda}\right)\left(\frac{\beta-\beta p}{1-\beta+\beta p}\right)\right\}^{b}\cdot A\cdot\pi_{(0)}-1=0. \tag{7}$$

We denote left part of (7) by $f(\beta)$. When $\beta=0$, or $f(\beta)=0$, we obtain $\pi_{(0)}=1/(1-\lambda)$, and $\pi_{(b)}=0$ for $1\le b\le B$. Then,

$$\begin{aligned}f(0) &= \frac{1}{1-\lambda}-1 \\ &= \frac{\lambda}{1-\lambda}>0.\end{aligned}$$

Also, when $\beta=1$, we can obtain $\pi_{(0)}=0$. So, $f(1)=-1<0$. Therefore, $f(\beta)$ has a solution satisfied with $0<\beta<1$.

After obtaining $\beta$ and $\pi_{(0)}$, we can calculate the total throughput $\Gamma$, *which is defined as the mean number of packets transmitted* into the ring per slot. $\Gamma$ is given by

$$\Gamma=N\cdot\gamma_{tr}. \tag{8}$$

Also, the mean queue length at node $i$, denoted as $L$, is expressed as

$$L=\sum_{b=1}^{B}b\cdot\pi_{(b)}. \tag{9}$$

The duration from the time that a packet arrives at a node until it is transmitted from the head of its node buffer is defined as mean access delay, $W$. By applying Little's formula, $W$ is obtained as

$$W=\frac{L}{\gamma_{tr}}. \tag{10}$$

The current evolution of wire-line LAN and MAN is towards high-speed Ethernet, which is standardized as the IEEE802.3z or IEEE802.3ae standards. The MAC protocol that we deal with in this paper is applied to the ring with high-speed Ethernet, and is able to support fair access among nodes. The main objective in this paper is to clarify performance of MAC protocol with multiple self-tokens in a slotted ring by an approximate discrete-time Markov chain model. We will make a comparison of our analytical model and computer simulation model in Section V, and show that our analytical and computer simulated approaches provide similar forecasts, and our analytical approach is valid for providing performance of MAC protocol with multiple self-tokens in a slotted ring. Furthermore, WDM technology is receiving recent attention because of its efficient use of bandwidth of optical fiber. Several MAC protocols have been proposed for WDM ring networks [11]–[13]. Our analysis can be useful and applicable to an approximate analysis for MAC protocols in the current and future WDM rings with optical add/drop multiplexer(OADM) and optical cross connect(OXC).

## IV. ADAPTIVE MAC PROTOCOL UNDER NON-UNIFORM TRAFFIC

When heavy load nodes continuously hold the transmission channel for a long time, or under non-uniform traffic, a throughput unfairness occurs. In such a situation, as the amount of self-tokens becomes large, most of the slots becomes occupied with packets transmitted by some nodes. Under non-uniform traffic, the amount of self-tokens should be dynamically allocated in order to achieve throughput fairness. In this section, we propose an adaptive MAC protocol for a slotted ring network under non-uniform traffic.

In the proposed adaptive MAC protocol, we define the duration of $R$ time slot as a *round*, and we focus on the behavior of node $i$ in round $k$. The following notations are used.

$T_i(k)$: The number of self-tokens which node $i$ can use during round $k$.

$T_i$: The number of self-tokens in node $i$'s self-token buffer.

$X_i$: The number of packets transmitted by node $i$ during each round.

$X_{th}$: The threshold for determining $T_i(k+1)$ at the end of round $k$.

At the beginning of each round, the values of $T_i$ and $X_i$ are set to $T_i(k)$ and zero, respectively. When node $i$ transmits a packet into the ring at a time slot, the value of $T_i$ is decreased by one, and $X_i$ is increased by one. Also, if node $i$'s self-token comes back to node $i$ from the ring, $T_i$ is increased by one.

Suppose that node $i$ is about to receive the slot from the ring at the beginning of a time slot. Node $i$ can transmit a packet into the ring if all following conditions are satisfied.

- The receiving slot is available.
- Node $i$ has at least one packet in the node buffer.
- $T_i$ is more than or equal to one.

In the proposed adaptive MAC protocol, node $i$ compares $X_i$ with $X_{th}$ at the end of round $k$. $T_i(k+1)$ is determined as follows.

*i)* If $X_i \le X_{th}, T_i(k+1) = T_i(k) + 1$.

*ii)* If $X_i > X_{th}, T_i(k+1) = T_i(k) - 1$.

After that, before round $k+1$ starts, the values of $T_i$ and $X_i$ are reset to $T_i(k+1)$ and zero, respectively.

Thus, in our proposed protocol the amount of self-tokens dynamically varies based on the number of packets transmitted during a round. So, the proposed protocol creates the situation where a node does not transmit a packet into the ring due to lack of a self-token, even though the node has some packets in its node buffer. That is, our proposed protocol can make free slots in the ring for the nodes which have small opportunity to transmit a packet. Therefore, the proposed protocol can achieve the throughput fairness even under non-uniform traffic.

Generally, the threshold-based mechanism causes total system throughput degradation. One way to increase total system throughput is to determine the threshold dynamically. However, since the slots in the ring are occupied with packets transmitted by some nodes, it is a disadvantage that the fairness performance dramatically degrades. Also, for an adaptive control of the threshold, each node has to get information about other nodes' throughputs. On the other hand, the threshold-based mechanism can achieve fair access to the ring without any information about other nodes' throughputs, while the total system throughput degrades a little. Therefore, we use the threshold-based mechanism in this paper.

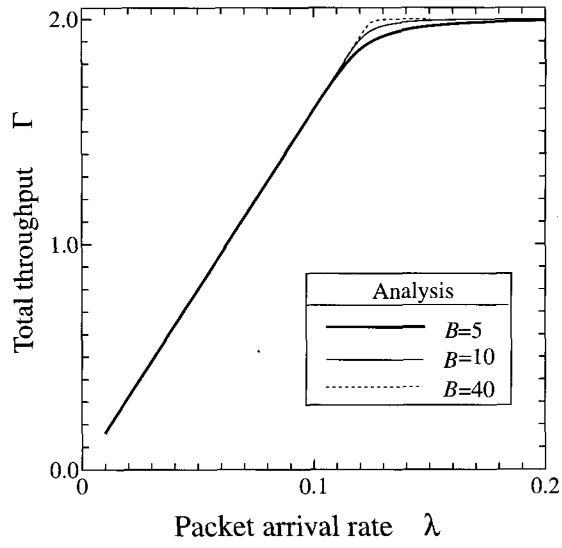


Fig. 3. Throughput versus arrival rate($N = 16$).

## V. NUMERICAL RESULTS

### A. Under Uniform Traffic

First, in order to clarify the accuracy of the analytical model described in Section III, we compare results of the analytical model with those of a computer simulation model under uniform traffic. The length of the ring is dozens of kilometers. It is assumed that the fixed packet length is $10^4$ bits, and the fixed aggregate transmission rate is 10 Gbps.

Fig. 3 shows the total throughput versus the packet arrival rate by the analytical model. This shows that, as $B$ becomes large, the total throughput reaches the maximum throughput sooner. Also, we can see from Fig. 3 that the throughput converges below $\lambda \cdot N$. The reason is that, when $\lambda$ is sufficiently large, the slots in the ring are always occupied with packets. So, a node can transmit a packet when the packet in the receiving slot destines itself. That is, the total throughput is given by $p \cdot N$=2. Therefore, the total throughput is given by min $\{\lambda \cdot N, p \cdot N\}$. In this paper, $B = 40$ is used in the following figures.

Fig. 4 shows the mean access delay versus the total throughput for the number of self-tokens in the case of $S = 32$. Lines and plots indicate results of an analytical model and a simulation model, respectively. $N = 16$ and $B = 40$ are set. When $T$ becomes large, computer simulated results approaches analytical ones, and tendency of the analytical results are consistent with that of the computer simulated ones. Therefore, we

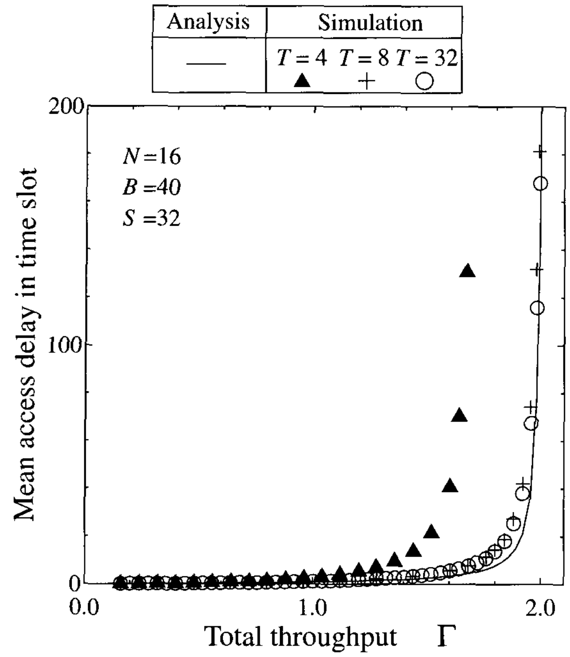


Fig. 4. Mean access delay versus total throughput for the number of self-tokens in the case of $S = 32 (N = 16,\ B = 40)$.

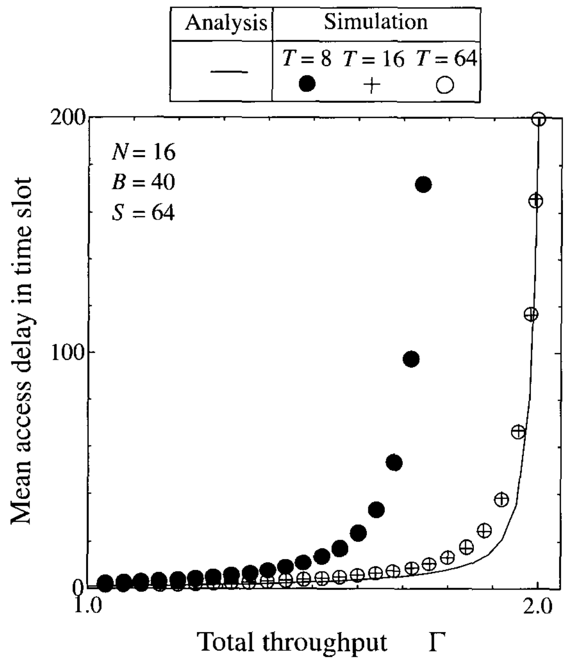


Fig. 5. Mean access delay versus total throughput for the number of self-tokens in the case of $S = 64 (N = 16,\ B = 40)$.

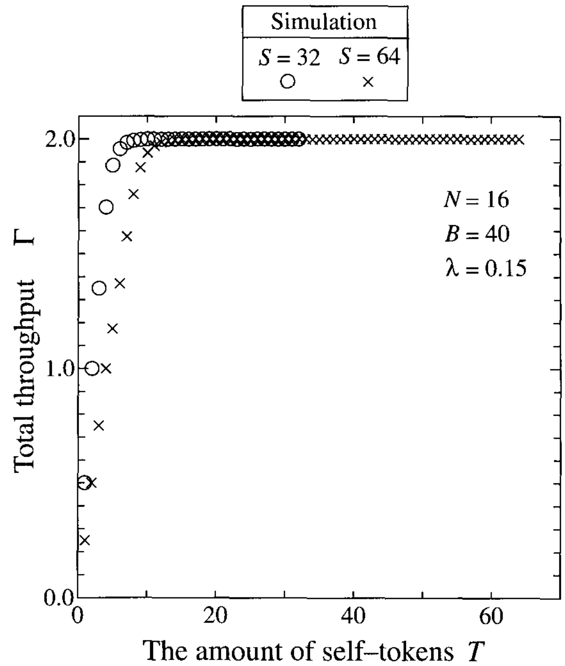


Fig. 6. Total throughput versus the number of self-tokens for the number of slots( $N = 16,\ B = 40,\ \lambda = 0.15$).

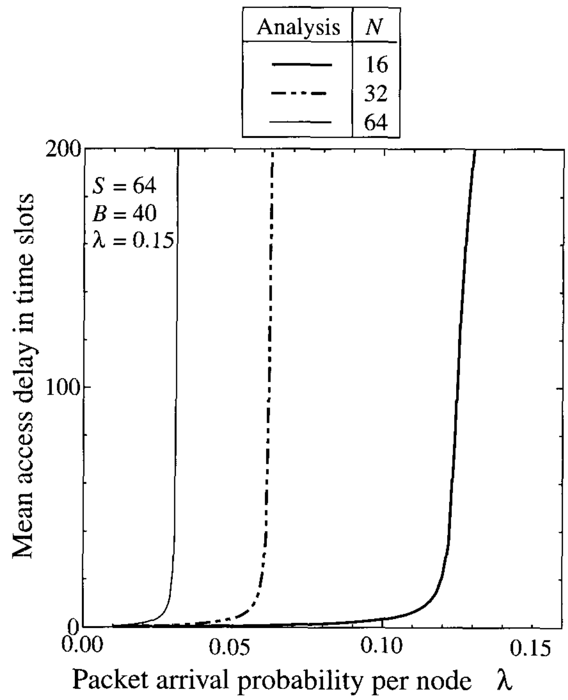


Fig. 7. Mean access delay versus the packet arrival probability with respect to the number of nodes($S = 64,\ B = 40,\ \lambda = 0.15$).

can show both propriety of approximate analytical model and validation of computer simulation results. In this regard, the analytical results are not completely consistent with that of the computer simulated ones. The reason for this is: In our analysis, it is assumed that the content of the slot received by a node are independent of the queue length at the node [3]. That is, it is regarded that the contents of the slot received by a node does not depend on the past behavior of the node. On the other hand, in the computer simulated model, all behaviors of nodes are simulated. Therefore, in these cases analytical results are not consistent with computer simulated ones.

Fig. 5 shows the mean access delay versus the total throughput for the number of self-tokens in the case of $S = 64$. Lines and plots indicate results of an analytical model and a simulation model, respectively. $N = 16$ and $B = 40$ are set. In the figure,

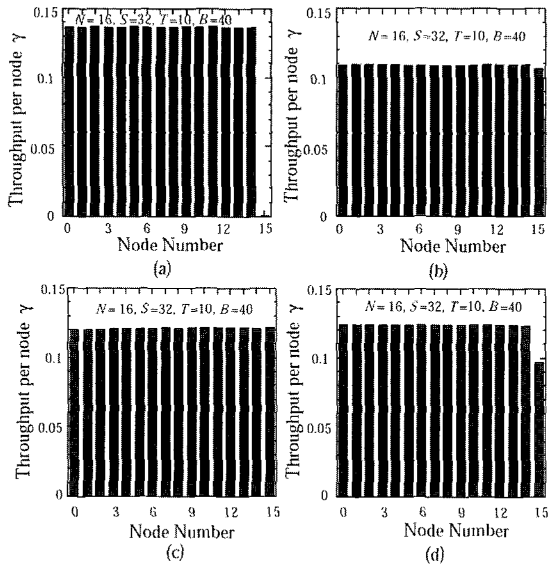


Fig. 8. Throughput per node under non-uniform traffic. ($N = 16$, $S = 32$, $T = 10$, $B = 40$): (a) Conventional, (b) proposed($R = 32, X_{th} = 4$), (c) proposed($R = 64, X_{th} = 8$), (d) proposed($R = 96, X_{th} = 12$).

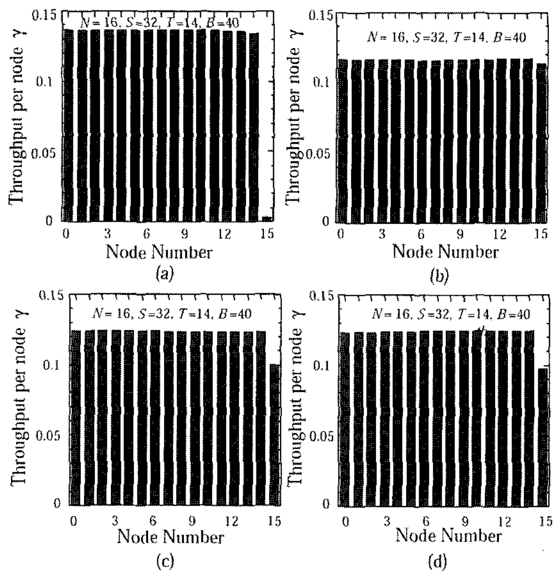


Fig. 9. Throughput per node under non-uniform traffic. ($N = 16$, $S = 64$, $T = 14$, $B = 40$): (a) Conventional, (b) proposed($R = 64, X_{th} = 8$), (c) proposed($R = 96, X_{th} = 12$), (d) proposed($R = 128, X_{th} = 16$).

as $T$ becomes large, the mean access delay becomes small for any total throughput $\Gamma$. This is because, with increasing $T$, the probability that a node cannot transmit a packet due to lack of a self-token becomes small.

Fig. 6 shows the throughput versus the number of self-tokens for the number of slots. $N = 16$, $B = 40$, and $\lambda = 0.15$ are set. The results show that the appropriate number of self-tokens for the value of $S$ should be set, so that the maximum throughput is achieved. For example, $T$ should be set to at least about ten and fifteen in the case of $S = 32$ and $S = 64$, respectively.

Fig. 7 shows the mean access delay versus the packet arrival probability with respect to the number of nodes by our analytical model. In the figure, as $N$ becomes large, the value of the packet arrival probability $\lambda$ enough to achieve the maximum total throughput becomes small. This is because as $N$ is large, the total number of arrival packets in a time slot becomes large for any $\lambda$.

## B. Under Non-Uniform Traffic

Next, we compare the results of the proposed protocol shown in Section IV with those of the conventional protocol [10] under non-uniform traffic by computer simulations. In the conventional protocol, the number of self-tokens is varied dynamically based on the duration which it takes for a self-token to round the ring. In both protocols, $N = 16$ and $B = 40$ are set. In a non-uniform traffic scenario [10],the packets arriving at node $i(i \neq 15)$ are not destined for node 15, and equally destined for node $j(i \neq j)$. The packets arriving at node 15 are equally destined for node $j(j \neq 15)$. Under this traffic, node 15 has less opportunity to transmit a packet, but the throughput fairness needs to be achieved.

Fig. 8 shows the throughput per node under non-uniform traffic by computer simulations. In all graphs, $N = 16$, $S = 32$, $T = 10$, and $\lambda = 0.2$ are set. Also, in the Fig. 9(b), (c), and (d), the values of $X_{th}/R$ are set at $1/N$, i.e., $X_{th}$ is in proportional to $R$. The reason is as follows. If $X_{th}$ is constant for any $R$, as $R$ increases, throughputs of nodes except for node 15 become small due to lack of a self-token. In such a situation, although the throughput of node 15 is almost identical for each value of $R$, the total throughput becomes small. Therefore, $X_{th}$ is in proportional to $R$ in this paper. In the conventional protocol shown in Fig. 8(a), the throughput of node 15 is much smaller than those of other nodes. The reason is as follows. In a slotted ring, a duration which it takes for a self-token to round the ring is always constant. That is, in the conventional protocol, the number of self-tokens dynamically varies in the slotted ring. Under the condition, the slots in the ring are almost occupied with packets for high load, and a node can transmit a packet when the receiving slot is free, or the packet in the receiving slot destines itself. Since node 15 does not receive any packets, it has less opportunity to transmit a packet. Therefore, the throughput of node 15 is much smaller than those of other nodes. On the other hand, in the proposed protocol shown in Fig. 8(b) and (c), the throughput of node 15 is almost the same as those of other nodes. This is because in the proposed protocol, a node compares the number of transmitted packets within a round with threshold $X_{th}$, while the number of self-tokens, which the node can use during a next round, dynamically varies. That makes free slots in the ring, and gives node 15 an opportunity to transmit a packet toward the ring. On the other hand, when $R = 96$ is set in the proposed protocol shown in Fig. 8(d), the throughput of node 15 is rather smaller than those of other nodes. In this case, an appropriate value of $R$ should be set.

Fig. 9 shows the throughput per node under non-uniform traffic in the case of $S = 64$ by computer simulations. In all graphs, $S = 64$, $T = 14$, and $\lambda = 0.2$ are set. Also, from the figure, we can find that in the case $R = 64$, the proposed protocol has a better performance with respect to the throughput per node.

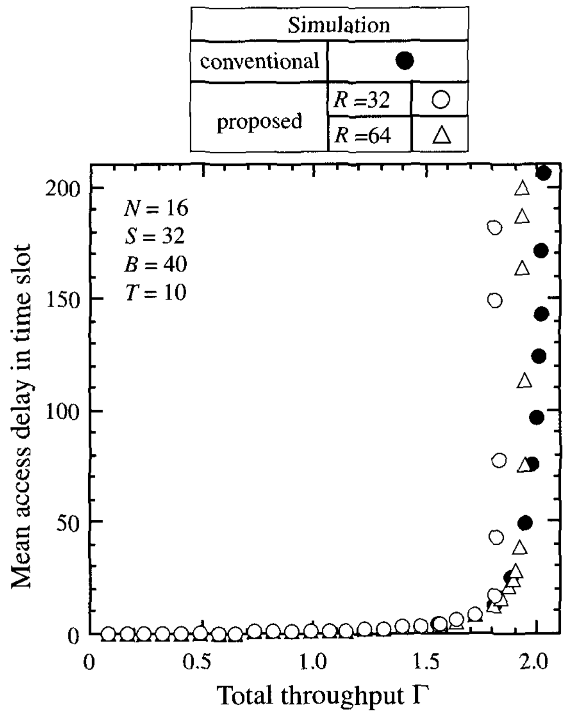


Fig. 10. Mean access delay versus total throughput under non-uniform traffic ($N = 16$, $S = 32$, $T = 10$, $B = 40$).

As $R$ becomes large, $X_{th}$ becomes large, thus the throughput of node 15 becomes small. Since the number of self-tokens at each node becomes large with increasing $X_{th}$, the nodes except for node 15 have more opportunities to transmit a packet within $R$ time slots, and the probability that node 15 can receive free slots from the ring becomes small. Therefore, the throughput of node 15 is small with increasing $R$.

Fig. 10 shows the mean access delay versus the total throughput under non-uniform traffic by computer simulations. The maximum throughput of the proposed protocol is smaller than that of the conventional one. This is because in the proposed protocol, a node might miss the opportunity to transmit a packet due to lack of a self-token. However, when $R = 64$ is set, the proposed protocol can achieve much better fair access than the conventional one with a little degradation of the delay-throughput performance. In this paper, the main objective of the proposed protocol is to equalize throughputs among nodes as fair as possible even under non-uniform traffic. From this point of view, our proposed protocol is effective for non-uniform traffic.

## VI. CONCLUSION

In this paper, we presented an analytical method for evaluating the delay-throughput performance for the MAC protocol with multiple self-tokens in a slotted ring under uniform traffic. Analytical results have the similar trend to computer simulated ones.

Furthermore, in order to achieve the throughput fairness under non-uniform traffic in a slotted ring, we proposed an adaptive MAC protocol in which the amount of self-tokens dynamically varies, based on the number of packets transmitted within a specified period. From computer simulated results, it is shown that our proposed protocol can achieve the throughput fairness under non-uniform traffic.

## APPENDIX

We derive the expression '$p = 2/N$' [3]. Suppose that node $i$ is about to receive the slot from the ring. $p$ is the probability that a node removes a packet from the receiving slot under the condition that the receiving slot is not free. Now, we consider the following two events in a symmetric slotted ring with $N$ nodes.

A: There is a packet in the slot received by node 0.

B: The packet in the slot received by node 0 destines node 0.

The throughput $\gamma$, which indicates the number of packets received by a node per slot, is given by

$$\gamma = P_r(\mathrm{A} \cap \mathrm{B}),$$

where $P_r(\mathrm{X})$ means the probability that event X occurs.

We denote by $\gamma^*$ the sum of throughput in node 0 and the average number of packets passing through node 0 per slot. In other words, $\gamma^* = P_r(\mathrm{A})$. We assume that traffic generated by a node is equally distributed toward other nodes. Recall a slotted ring shown in Fig.1. When the packet in the slot received by node 0 comes from node $i (i \neq 0)$, the probability that the packet destines node 0 is $N - i/(N-1)$. Then, $\gamma^*$ is given by the following equation.

$$\gamma^* = \gamma \sum_{i=1}^{N-1} \frac{N-i}{N-1} = \frac{\gamma N}{2}.$$

Therefore, we obtain

$$p = P_r(B|A) = \frac{P_r(\mathrm{A} \cap \mathrm{B})}{P_r(\mathrm{A})} = \frac{2}{N}.$$

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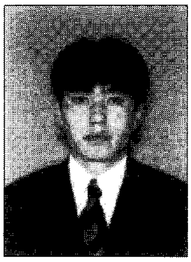

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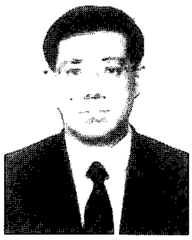

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