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優先メッセージが加わるトークンリングシステムの近似解析

木村　丈治
ＮＴＴ交換システム研究所

本報告では、優先クラスの異なる２種類のメッセージが各局に加わる非対称形制限式トークンリングシステムのトラヒック特性を近似解析している。各局において、優先クラスの高いメッセージは優先クラスの低いメッセージに対し、非割り込み優先権を持つとし、各優先クラスのメッセージは、それぞれ集団で到着し、その到着間隔は一般分布に従うとする。トラヒック特性を評価するため、トークンリングシステムを巡回形多重待ち行列としてモデル化し、そのモデルを待ち行列理論と拡散近似の手法を用いて解析している。数値例では、シミュレーションとの比較により、本近似法の妥当性を示している。

APPROXIMATIONS FOR A GENERAL TOKEN RING SYSTEM WITH PRIORITY CLASSES OF MESSAGES

George KIMURA

NTT Communication Switching Laboratories

3-9-11, Midoricho, Musashino-shi, Tokyo, 180 Japan

This paper presents new approximation methods for evaluating the performance of a token ring system with limited service, where two priority classes of messages are offered in batches at each station. In order to obtain performance measures, the system is regarded as multiqueue model with the nonpreemptive priority. Our model can handle general batch input streams. The performance measures are derived using the queueing theory and the diffusion approximation technique. The proposed approximations are numerically validated by comparing them with simulation results.

1. INTRODUCTION

Token ring systems are commonly used in local area networks (LANs) [1], [2]. This paper presents a method for evaluating the performance of a token ring system with limited service offering two priority classes of messages. In this system, there are N stations in the ring and a token is passed in cyclic order (see [3], [4], [5]).

Recently, the importance of priority functions in LANs is increasing [6]. Therefore, several priority schemes for token ring systems have been proposed [6], [7]. This paper deals with message-based priority which means that priority is assigned to the message. Namely, we assume priority classes of messages will be offered to a token ring system.

There has been much interest in token ring systems with message-based priorities. Yamamoto et al. [8] and Shen et al. [9] have proposed priority schemes. In their performance models, the gated policy is adopted and the message buffer (queue) capacity in each station is assumed to be only one message. Their approach cannot be extended to a model which allows infinite buffer capacity. Nishida et al. [10] have proposed another priority scheme and analyzed it under the conditions of mixed exhaustive and limited policies, and infinite buffer capacity in each station. However, according to Sethi et al. [11], "the current trend in the token ring system is moving toward a round-robin system." A round-robin system is another term for the limited policy. Karvelas et al. [12] have treated the token ring system with two priority classes of messages and analyzed it under the conditions of batch Poisson inputs and limited service. They applied their results to the analysis of integrated packet voice/data systems. However, it is well known that the voice packet arrival stream cannot be modeled as batch Poisson input [13]. The problem is lack of a method that allows general batch input. The goal of this paper is to resolve the problem by presenting new approximations that are capable of handling general batch input.

2. MODEL DESCRIPTION

In order to evaluate performance measures for a token ring system with limited service and message-based priority, a multiqueue model is proposed. In queueing terminology, the token is the server, messages or packets are the customers, and the overhead associated with sending a token from one station to the next is the walking time. A symmetric multiqueue model means that the arrival process, the service time and the walking time distributions at each queue are identical.

The multiqueue model considered here can be characterized by the following assumptions:

1) The single server walks around among N queues (LAN stations);

2) When the server arrives at the i-th queue and finds no waiting customers, it moves to the subsequent (i+1)-th queue. If the server finds waiting customers, it serves the first customer in the queue and then moves on to the subsequent (i+1)-th queue, $1 \leq i \leq N$ (when the server is in the N-th queue, it moves on to the first queue);

3) There are two priority classes of customers, 1 and 2. Class 1 has priority over class 2. Interarrival times of batches (messages) for class j customers at the i-th queue are independently and identically distributed (iid) random variables with a mean of λ_{ji}^{-1}, and a variance of σ_{Aji}^{2}. Batch sizes for class j (the number of customers in arriving class j batches) are

iid random variables with a mean of b_{ji} and a variance of σ_{Bji}^2 ($1\le i\le N$; $j=1,2$). By letting $b_{ji}^{(2)}$ be the second moment of the batch size, $b_{ji}^{(2)}=\sigma_{Bji}^2+b_{ji}^2$.

4) The priority rule is of the non-preemptive [12] or the head-of-the line. Namely, class 2 customers can be served only when the arriving server at the i-th queue finds no waiting class 1 customers. Once a class 2 customer receives his service, class 1 customers cannot interrupt the service of class 2 customers even if the class 1 customers arrive at the i-th queue during the service time.

5) The customers are served individually, based on FIFO (first-in first-out) rule among arrival batches and on SIRO (service in random order) rule within a batch.

6) The service times for class j customers arriving at the i-th queue are iid random variables with a mean of h_{ji}, a variance of σ_{Hji}^2, and the second moment $h_{ji}^{(2)}$, $1\le i\le N$.

7) The walking times from the i-th queue to the (i+1)-th queue are iid random variables with a mean of u_i and a variance of σ_{Ui}^2, $1\le i\le N$.

Remarks: 1) If $\lambda_{1i}=0$ or $\lambda_{2i}=0$ (no priority classes), then the model considered here is reduced to that of Kimura et al. [14] and Kuehn [15].

2) If $\lambda_{1i}^2\sigma_{A1i}^2=1$ and $\lambda_{2i}^2\sigma_{A2i}^2=1$ (batch Poisson inputs), then the model is consistent with that of Karvelas et al. [12].

The following notations are needed to sketch the analysis;

$$c_0=\sum_{i=1}^{N} u_i\ ,\quad \rho_i=\sum_{j=1}^{2}\lambda_{ji}b_{ji}h_{ji}\ ,\quad \rho_0=\sum_{i=1}^{N}\rho_i\ .$$

$E(VW_{ji})$: mean virtual waiting time of class j customers in the i-th queue,

$E(W_{ji})$: mean actual waiting time of class j customers in the i-th queue,

$E(WB_{ji})$: mean actual waiting time of a class j customer in the i-th queue whose position is the first in its batch,

$E(Q_{ji})$: mean queue length of class j customers in the i-th queue,

$E(\widetilde{VW}_{ji})$: mean virtual waiting time for a $GI^{[x]}/G/1$ ordinary queue with arrival rate λ_{ji} and mean service time $\hat{c}_{ji}$,

$E(\widetilde{WB}_{ji})$: mean actual waiting time of a customer whose position is the first in its batch for a $GI^{[x]}/G/1$ ordinary queue with arrival rate λ_{ji} and mean service time $\hat{c}_{ji}$,

c: mean cycle time which is known that $c=\frac{c_0}{1-\rho_0}$.

$c_i^{(2)}$: second moment of cycle time which is given approximately by Kuehn[15],

$\hat{c}_{ji}$: mean conditional cycle time assuming that a class j customer of the i-th queue contributes to the service time of the cycle, given by

$$\hat{c}_{ji}=\frac{c_0+h_{ji}}{1-\rho_0+\rho_i}\ .$$

$\hat{c}_{ji}^{(2)}$: second moment of conditional cycle time assuming that a class j customer of the i-th queue contributes to the service time of the cycle, given approximately by Kuehn[15],

$$\hat{c}_{ji}^{(2)} = \sum_{k=1}^{N} \sigma_{Uk}^2 + \sum_{\substack{k=1 \\ k \neq i}}^{N} (\hat{a}_{ijk} h_{ik}^{(2)} - \hat{a}_{ijk}^2 h_{ik}^2) + \sigma_{Hji}^2 + \hat{c}_{ji}^2 .$$

$\hat{\hat{c}}_i$: mean conditional cycle time assuming that no customer of the i-th queue contributes to the service time of the cycle, given by

$$\hat{\hat{c}}_i = \frac{c_0}{1-\rho_0+\rho_i} .$$

$\hat{\hat{c}}_i^{(2)}$: second moment of conditional cycle time assuming that no customer of the i-th queue contributes to the service time of the cycle, given approximately by Kuehn[15],

$$\hat{\hat{c}}_i^{(2)} = \sum_{k=1}^{N} \sigma_{Uk}^2 + \sum_{\substack{k=1 \\ k \neq i}}^{N} (\hat{\hat{a}}_{ik} h_{ik}^{(2)} - \hat{\hat{a}}_{ik}^2 h_{ik}^2) + \hat{\hat{c}}_i^2 .$$

where

$$\hat{a}_{ijk} = (\lambda_{1k} b_{1k} + \lambda_{2k} b_{2k}) \hat{c}_{ji}, \quad \hat{\hat{a}}_{ik} = (\lambda_{1k} b_{1k} + \lambda_{2k} b_{2k}) \hat{\hat{c}}_i ,$$

$$a_{1i} = \lambda_{1i} b_{1i} c, \quad a_{2i} = \lambda_{2i} b_{2i} c, \quad a_i = (\lambda_{1i} b_{1i} + \lambda_{2i} b_{2i}) c .$$

3. ANALYSIS

In this section, two approximation methods are proposed. In approximation 1, individual mean waiting times for the high and low priority classes are obtained from the virtual waiting times. In approximation 2, the total virtual load in each queue is approximated by a diffusion process in almost the same manner as Ref.[14]. The mean waiting time for the high priority class is derived in the same manner as in approximation 1. The mean waiting time for the low priority class is obtained using a relationship between the virtual load and the waiting time.

3.1 Approximation 1

Consider the virtual waiting time for class 1, $E(VW_{1i})$. $E(VW_{1i})$ is given by the sum of $E(Q_{1i}) \cdot \hat{c}_{1i}$ and the mean forward recurrence time of the cycle time. This produces

$$E(VW_{1i}) = E(Q_{1i}) \hat{c}_{1i} + a_{1i} \frac{\hat{c}_{1i}}{c} \cdot \frac{\hat{c}_{1i}^{(2)}}{2\hat{c}_{1i}} + a_{2i} \frac{\hat{c}_{2i}}{c} \cdot \frac{\hat{c}_{2i}^{(2)}}{2\hat{c}_{2i}} + (1-a_{1i}-a_{2i}) \frac{\hat{\hat{c}}_i}{c} \cdot \frac{\hat{\hat{c}}_i^{(2)}}{2\hat{\hat{c}}_i} . \tag{1}$$

From Little's formula,

$$E(Q_{1i}) = \lambda_{1i} b_{1i} E(W_{1i}) . \tag{2}$$

The relationship between $E(W_{1i})$ and $E(WB_{1i})$ is represented by

$$E(W_{1i}) = E(WB_{1i}) + \frac{b_{1i}^{(2)} - b_{1i}}{2b_{1i}} \hat{c}_{1i} . \tag{3}$$

Substituting (2) and (3) into (1), it follows that

$$E(VW_{1i}) = \lambda_{1i} b_{1i} \hat{c}_{1i} \{E(WB_{1i}) + \frac{b_{1i}^{(2)} - b_{1i}}{2b_{1i}} \hat{c}_{1i}\} + a_{1i} \frac{\hat{c}_{1i}}{c} \cdot \frac{\hat{c}_{1i}^{(2)}}{2\hat{c}_{1i}} + a_{2i} \frac{\hat{c}_{2i}}{c} \cdot \frac{\hat{c}_{2i}^{(2)}}{2\hat{c}_{2i}} + (1-a_{1i}-a_{2i}) \frac{\hat{\hat{c}}_i}{c} \cdot \frac{\hat{\hat{c}}_i^{(2)}}{2\hat{\hat{c}}_i} . \tag{4}$$

Now assume that the difference between $E(VW_{1i})$ and $E(WB_{1i})$ equals that between $E(\widetilde{VW}_{1i})$ and $E(\widetilde{WB}_{1i})$ for a $GI^{[x]}/G/1$ ordinary queue; i.e.,

$$E(VW_{1i}) - E(WB_{1i}) = E(\widetilde{VW}_{1i}) - E(\widetilde{WB}_{1i}) . \tag{5}$$

By applying the diffusion approximation technique, the right-hand side of (5) can be evaluated. $E(\widetilde{VW}_{1i})$ and $E(\widetilde{WB}_{1i})$ are given by[16]

$$E(\widetilde{VW}_{1i}) = \frac{\lambda_{1i}}{2}\{(b_{1i}^{(2)}-b_{1i})\hat{c}_{1i}^2+b_{1i}\hat{c}_{1i}^{(2)}\}$$
$$+\frac{\lambda_{1i}b_{1i}\hat{c}_{1i}^3}{2(1-\lambda_{1i}b_{1i}\hat{c}_{1i})}\{\lambda_{1i}^2\ \sigma_{A1i}^2 b_{1i}^2+\sigma_{B1i}^2+b_{1i}\frac{(\hat{c}_{1i}^{(2)}-\hat{c}_{1i}^2)}{\hat{c}_{1i}^2}\}, \quad (6)$$
$$E(\widetilde{WB}_{1i}) = \frac{\lambda_{1i}b_{1i}\hat{c}_{1i}^3}{2(1-\lambda_{1i}b_{1i}\hat{c}_{1i})}\{\lambda_{1i}^2\ \sigma_{A1i}^2 b_{1i}^2+\sigma_{B1i}^2+b_{1i}\frac{(\hat{c}_{1i}^{(2)}-\hat{c}_{1i}^2)}{\hat{c}_{1i}^2}\}. \quad (7)$$

By substituting (4), (6) and (7) into (5), $E(WB_{1i})$ can be obtained. Then using (3), the mean waiting time for class 1, $E(W_{1i})$, is derived.

The mean waiting time for class 2 can be obtained in the same manner as for class 1. The virtual waiting time for class 2, $E(VW_{2i})$, is obtained by

$$E(VW_{2i})=\lambda_{2i}b_{2i}\hat{c}_{2i}E(W_{2i})+\lambda_{1i}b_{1i}\hat{c}_{1i}E(WB_{2i})+\lambda_{1i}b_{1i}\hat{c}_{1i}E(W_{1i})$$
$$+a_{1i}\frac{\hat{c}_{1i}}{c}\cdot\frac{\hat{c}_{1i}^{(2)}}{2\hat{c}_{1i}}+a_{2i}\frac{\hat{c}_{2i}}{c}\cdot\frac{\hat{c}_{2i}^{(2)}}{2\hat{c}_{2i}}+(1-a_{1i}-a_{2i})\frac{\hat{c}_i}{c}\cdot\frac{\hat{c}_i^{(2)}}{2\hat{c}_i}. \quad (8)$$

The following relationship between $E(W_{2i})$ and $E(WB_{2i})$ can be shown:

$$E(W_{2i})=E(WB_{2i})+\frac{\hat{c}_{2i}}{1-\lambda_{1i}b_{1i}\hat{c}_{1i}}\cdot\frac{b_{1i}^{(2)}-b_{1i}}{2b_{1i}}. \quad (9)$$

Making the same assumption for the difference between the virtual waiting time and the actual waiting time results in

$$E(VW_{2i})-E(WB_{2i})=E(\widetilde{VW}_{2i})-E(\widetilde{WB}_{2i}). \quad (10)$$

$E(\widetilde{VW}_{2i})$ and $E(\widetilde{WB}_{2i})$ are given by diffusion approximation in the same manner. Using (8), (9) and (10), the mean waiting time for class 2, $E(W_{2i})$ is obtained.

Remark: In the case of batch Poisson inputs ($\lambda_{1i}^2\sigma_{A1i}^2=1$ and $\lambda_{2i}^2\sigma_{A2i}^2=1$), our approximate formulas are consistent with the results of Karvelas et al. [12].

3.2 Approximation 2

Assume that the service time distribution is independent of priority class, i.e., $h_{1i}=h_{2i}=h_i$, $\sigma_{H1i}^2=\sigma_{H2i}^2=\sigma_{Hi}^2$.

Consider the i-th queue and fix the time point t. Let $VL_i(t)$ denote the total virtual load of queue i at time t. The range of $VL_i(t)$ is then a half-open interval $[0,\infty)$. $VL_i(t)$ can then be regarded as a diffusion process with pdf $f_i(x,t)$, i.e.,

$$f_i(x,t)dx = \Pr\{x \leq VL_i(t) < x+dx\}. \quad (11)$$

Let $L_i(t)$ be the work load arriving at the queue in $(0,t]$. Let $Y_i(t)$ be the number of times that the server has visited the queue in $(0,t]$, and $Z_i(t)$ be the $Y_i(t)$-th convolution of the service time. Let us define $VL_i'(t)$ as follows:

$$VL_i'(t)=L_i(t)-Z_i(t)+VL_i(0). \quad (12)$$

The stochastic process $VL_i'(t)$ is referred to as an unrestricted process (see e.g. [17]) and its range is the open interval $(-\infty,\infty)$.

For approximating the stochastic process (in this case, the virtual load) by diffusion processes, a boundary condition is necessary. We set the elementary return boundary at the origin (x=0). This paper will approximate the sojourn time distribution at the origin by an exponential distribution as in Ref.[16]. Let π_{i0} be the probability that a diffusion particle sojourns at the origin and $q_i(x)$ be the pdf for jump amounts from the origin. A jump amount corresponds to a work load that is carried in the i-th queue by the first arriving batch after the queue becomes empty (see also Ref.[14] and [16]). The following set of equations must be satisfied by $f_i(x,t)$:

$$\frac{\partial f_i}{\partial t} = -\alpha_i \frac{\partial f_i}{\partial x} + \frac{\beta_i}{2}\cdot\frac{\partial^2 f_i}{\partial x^2} + (\lambda_{1i}+\lambda_{2i})\ \pi_{i0}(t) r_i(x)\ , \tag{13}$$

$$\frac{d\pi_{i0}(t)}{dt} = -(\lambda_{1i}+\lambda_{2i})\ \pi_{i0}(t) + [-\alpha_i f_i + \frac{\beta_i}{2}\cdot\frac{\partial f_i}{\partial x}]_{x=0}, \tag{14}$$

$$\lim_{x\to 0} f_i(x,t) = \lim_{x\to\infty} f_i(x,t) = 0, \tag{15}$$

where α_i, β_i are the diffusion parameters given by[16]:

$$\alpha_i = \lim_{t\to\infty} E(VL_i'(t))/t = (\lambda_{1i}b_{1i} + \lambda_{2i}b_{2i})\ h_i - h_i \,/\hat{c}_i\ , \tag{16}$$

and

$$\beta_i = \lim_{t\to\infty} Var(VL_i'(t))/t = \{\lambda_{1i}(b_{1i}^2+\sigma_{B1i}^2)+\lambda_{2i}\ (\lambda_{2i}^2\ \sigma_{Ai}^2 b_{2i}^2+\sigma_{B2i}^2)-\frac{\sigma_{\hat{c}i}^2}{\hat{c}_i^3})h_i^2 + (\lambda_{1i}b_{1i} + \lambda_{2i}b_{2i} - \frac{1}{\hat{c}_i})\ \sigma_{Hi}^2\ . \tag{17}$$

Solving the diffusion equation (13) under the conditions (14) and (15), the mean virtual load $E(VL_i)$ is obtained by[14]

$$E(VL_i) = \frac{\hat{c}_i}{2h_i}\sum_{j=1}^{2}\lambda_{ji}\{(b_{ji}^{(2)} - b_{ji})h_i + b_{ji}h_i^{(2)} - \frac{\beta_i}{\alpha_i} h_i b_{ji}\}\ . \tag{18}$$

The mean waiting time for class 1 is obtained in the same manner as in approximation 1.

The mean waiting time for class 2 is derived as follows. The relationship between the virtual load and the waiting time for the multiqueue problem is given by

$$E(VL_i) = \sum_{j=1}^{2}\ [\lambda_{ji}b_{ji}h_i E(WB_{ji}) + \lambda_{ji}b_{ji}h_i^{(2)} + \frac{b_{ji}^{(2)} - b_{ji}}{2}\ \lambda_{ji}h_i\hat{c}_i\ ]\ . \tag{19}$$

Equation (19) is derived by using Brumelle's theorem [18] (see also Ref.[8]). The mean waiting time $E(WB_{2i})$ is then obtained as follows:

$$E(WB_{2i}) = \frac{1}{\lambda_{2i}b_{2i}h_i}\ [E(VL_i) - \lambda_{1i}b_{1i}h_i E(WB_{1i}) + \sum_{j=1}^{2}(\frac{\lambda_{ji}b_{ji}}{2}\ h_i^{(2)} + \frac{b_{ji}-b_{ji}}{2}\ \lambda_{ji}h_i\hat{c}_i\ )]. \tag{20}$$

The mean waiting time for an arbitrary class 2 customer $E(W_{2i})$ is obtained in the same manner as section 3.1:

$$E(W_{2i}) = E(WB_{2i}) + \frac{b_{2i}^{(2)} - b_{2i}}{2b_{2i}}\cdot\frac{\hat{c}_i}{1-\lambda_{1i}b_{1i}\hat{c}_i}\ . \tag{21}$$

Let $E(Q_{ji})$ be the mean number of class j customers in the i-th queue for $1 \le i \le N$; j=1,2. Applying the well-known Little's formula, we have

$$E(Q_{ji}) = \lambda_{ji}b_{ji}E(W_{ji})\ ,\ j=1,2\ . \tag{22}$$

4. NUMERICAL EXAMPLES

The proposed approximation results are numerically validated by comparing them with simulation results. Throughout the following examples, it is assumed that N=10, u_i=0.1, and σ_{Ui}^2=0 ($1 \le i \le N$). This situation, for example, corresponds to a token ring system with a distance between adjacent stations of 200 (m), a signal propagation velocity of 2 10^8 (m/s), a transmission rate of 100 (Mb/s), and a mean packet length of 1000 (bits).

Figure 1 shows the results of the mean waiting times vs. a_i for a symmetric $E_2^{[x]}, E_2^{[x]}/D/1$ multiqueue ($h_{1i}=h_{2i}=1$, $\sigma_{H1i}^2=\sigma_{H2i}^2=0$). Here, [x] represents the batch size distribution. The batch sizes for both classes are assumed to be identical and have a unit distribution ($b_{1i}=b_{2i}=4$, $\sigma_{B1i}^2=\sigma_{B2i}^2=0$). It can be seen from the figures that the mean waiting time approximation for the high priority class (class 1) is very accurate. Concerning the accuracy of the mean waiting time approximation for the low priority class (class 2), approximation 2 is better than approximation 1.

Figure 2 shows the results of the mean waiting time vs. a_i for a nonsymmetric ($\rho_1=10\rho_2$, $\rho_2=\cdots=\rho_{10}$) $H_2,E_2/D/1$ multiqueue ($h_{1i}=h_{2i}=1$, $\sigma_{H1i}^2=\sigma_{H2i}^2=0$). It is seen that our results are suffciently accurate for class 1, and both approximations, 1 and 2, show good results for class 2, except for station 1.

Figure 3 shows the result of the mean waiting time vs. a_i for a symmetric $H_2,E_2/D_1,D_2/1$ multiqueue ($h_{1i}=0.5$, $h_{2i}=1$, $\sigma_{H1i}^2=\sigma_{H2i}^2=0$). The accuracy of approximation 1 seems sufficient for the different service time model.

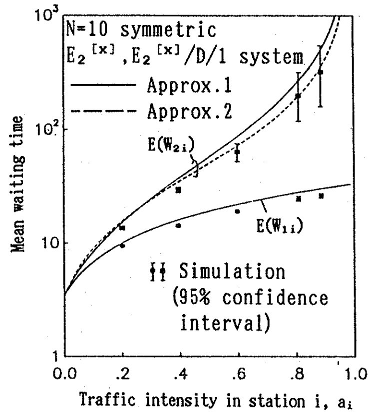
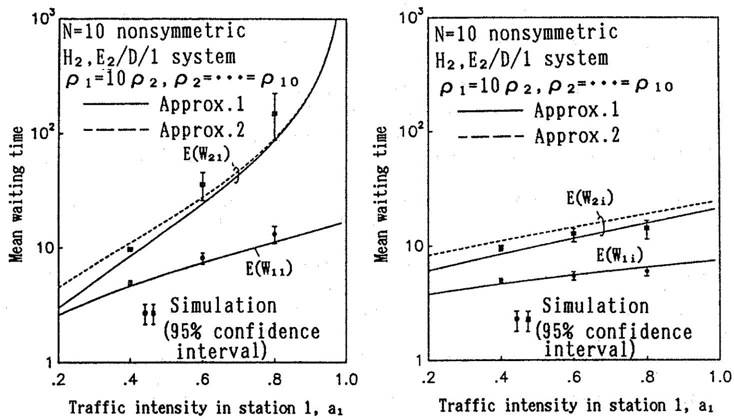


Fig.1 Mean waiting time in the symmetric $E_2^{[x]}, E_2^{[x]}/D/1$ system.



(a) Station 1. (b) Station 2-10.

Fig.2 Mean waiting time in the nonsymmetric $H_2,E_2/D/1$ system.

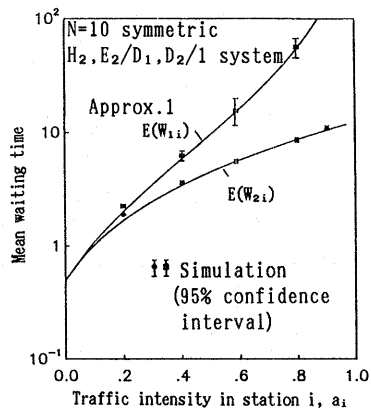


Fig.3 Mean waiting time in the symmetric $H_2,E_2/D_1,D_2/1$ system.

5. CONCLUSION

This paper presented approximations for a token ring system with limited service where two priority classes of messages were offered in batches and nonpreemptive priority was considered. The proposed approximate formulas are very simple for an arbitrary number of queues and any traffic pattern. The accuracy of the approximation is validated through numerical examples. In consequence, it is clear that the accuracy of this approximation is sufficient for practical use.

The following topics remain for further study:

(1) Derivation of the n-th moment of the waiting time and the number of customers in the queues, $n \geq 2$.

(2) An expansion to a general model which allows an arbitrary maximum number of customers from any queue that can be served per cycle.

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