A DELAY MODEL FOR PRIORITY CLASSES OF FDDI BASED ON M/G/1 WITH VACATIONS

by
Priya N. Werahera, Anura P. Jayasumana and **Duane C. Boes***
Department of Electrical Engineering
*Department of Statistics
Colorado State University
Fort Collins, CO 80523

Abstract
The classical M/G/1 system with vacations has been used to estimate the mean waiting time of individual priority classes of homogeneous FDDI networks. To faithfully model the FDDI network using M/G/1 system, the vacation interval of the server (token) as seen by individual priority classes must be evaluated. The expressions for the mean waiting time of individual priority classes are functions of first and second moments of the vacation intervals of that class. It can be shown that the expression derived for the first and second moments of the vacation intervals of the respective classes are functions of mean and variance of number of messages transmitted by each priority class per token rotation. These expressions are evaluated using an iterative procedure that utilizes the prior knowledge of the throughput characteristics of the FDDI network. Simulation results show that the model provides accurate estimates for the mean waiting time of individual priority classes of a homogeneous FDDI network.
Key words: FDDI, M/G/1 Model with vacations, mean waiting time

1 Introduction

Analysis of timed-token protocols such as FDDI is very difficult due to the cycle dependancy of the message transmissions. As a result the analytical models available to evaluate the charcteristics of timed-token protocols with multiple classes of priorities are limited in scope. Models are available to evaluate the throughput characteristics of FDDI networks with multiple classes of priorities [DyBu88, Tang91, KaLe92, JaWe90, WeJa94].

The early analytical results on the delay performance of FDDI networks are given in [KaLe88, Taka90]. In [TaSa91], an expression for the mean message delay of a single asynchronous class in an FDDI network is given. A gated limited M/G/1 vacation model has been developed in [GeVa89] for the IEEE 802.4 token bus standard. The results of [GeVa89] has been extended in [GeVa90], to evaluate the mean waiting time of synchronous traffic of an FDDI network. An M/G/1 vacation model has been successfully utilized in [Lama91] to obtain mean waiting time for messages in an FDDI network with single asynchronous class. This model is an extension of the exhaustive limited M/G/1 vacation model analyzed in [Lee89]. The models described in [GeVa89] and [Lee89] considered a service discipline in which the limit on the number of frames that can be served in a token visit is fixed. However, in [Lama91], an M/G/1 vacation model has been proposed that uses a limit that varies from visit to visit. Numerical techniques have been used to solve the expression for the mean waiting time [Lama91]. The M/G/1 vacation model in this paper is used without any service restrictions applied as described in [Lee89, GeVa89, Lama91]. The service restrictions are used in the above models to analytically evaluate the first two moments of the vacation interval. The model described in this paper and the nonpreemptive priority delay model described in [WeJB95] utilize the prior knowledge of the throughput characteristics to estimate the vacation interval.

Section 2 briefly outlines the medium access protocol of FDDI networks. A brief description of the M/G/1 vacation model is given in Section 3 and the relationship between vacation time, token cycle-time and service time, and expressions for the first two moments of the vacation time are derived in Section 4.

The procedure for evaluating the mean waiting time is given in Section 5. The results of the M/G/1 vacation model for delay performance of FDDI networks is presented in Section 6 and a summary is given in Section 7.

2 FDDI Ring Operating Procedure

Each station maintains two timers, TRT and THT. TRT at node j is used to time the interval taken by the token to circulate around the ring starting from node j. If a station captures the token before its TRT reaches the value of $TTRT$, it is an "early" token. If it captures the token after TRT has exceeded the value of $TTRT$, then it is a "late" token. When node j captures an "early" token, TRT is reset and restarted immediately. Before resetting TRT, its current value is assigned to THT. TRT becomes active during message transmission and THT becomes active only during asynchronous message transmission at node j. THT is reset when the token is passed to the next station, and it becomes inactive while TRT continues to run until the token arrives at node j again. When node j recaptures a "late" token, TRT is not reset, but is allowed continue in order to accumulate the "lateness" of the network.

For an "early" token, the station is allowed to transmit asynchronous traffic provided the current value of THT is less than the value of $TTRT$. The difference between the current value of THT and $TTRT$ determines the asynchronous bandwidth available to this station. However, a station cannot hold the token longer than $TTRT$ to initiate any message transmission. It has been stated that the protocol guarantees an average response time for synchronous traffic not greater than $TTRT$, and a maximum response time not greater than twice the $TTRT$ [MAC87, SMT89, SeJo86, John87].

FDDI standard also supports a priority scheme for asynchronous traffic. Each priority class at a station has a threshold value $T\_Pri(i)$ $(i = 1, .., n)$. Class 1 is assumed to have the highest priority, and class n the lowest priority among asynchronous classes of traffic. Transmission of messages of an asynchronous class begins with class 1 and continues with the lower priority classes sequentially. The asynchronous traffic of class i may only be transmitted if the current value of THT is less than the class threshold value $T\_Pri(i)$. Since the difference between the current value of THT and $TTRT$ reflects the asynchronous bandwidth, the maximum value that can be assigned to $T\_Pri(i)$ of class i is restricted to $TTRT$. If there are no messages in class i, or if the THT has exceeded the $T\_Pri(i)$, then the next lower class is served. A new token is issued when there are no more messages, or the lowest priority class has been served according to the above scheme.

3 M/G/1 Queueing System with Vacations

The notation used in this paper is summarized in Tables 1 and 2. Using the M/G/1 queueing system with vacations, the mean waiting time of priority class j of FDDI network can be written as:

$$W_j = \frac{1}{2}\frac{\lambda_j \bar{X_j^2}}{(1 - \rho_j)} + \frac{1}{2}\frac{\bar{V_j^2}}{\bar{V_j}} . \qquad (1)$$

where λ_j is the normalized arrival rate, $\bar{X_j^2}$ is the second moment of the service time, ρ_j is the normalized utilization, $\bar{V_j}$ is the first moment of the vacation time and $\bar{V_j^2}$ is the second moment of the vacation time of class j. A proof for Equation 1 can be found in [BeGa87, Klei75]. Tables 1 and 2 provide a summary of notation used in this paper.

4 Vacation Time and Service Time of Priority Classes

Figure 1 shows the relationship of service time Z_j of class j at node 1 and token-cycle time C_j' (measured from class j) to the vacation time V_j during the rth and $r+1$th visit of the token. The vacation time V_j is defined as the time elapsed from the instant a priority class at a station releases the token till the next instant the same priority class at the same station receives the token. Hence, V_j, C_j' and Z_j are given by:

$$V_j = C_j' - Z_j . \qquad (2)$$

4.1 Effect of the Priorities on Service Time

The service time Z_j received by each priority class is affected by the priority mechanism of FDDI networks as described in [WeJB95]. This analysis can be extended for M/G/1 queueing system with vacations.

Figure 2 shows the messages transmitted by class 0 during rth and $r+1$th visit of the token. Let the current value of the TRT be C_0' and the previous value of TRT at this station be C_b. Note that, message

Table 1: Notation-I

C	Token-cycle time
$\bar{C}$	Mean token-cycle time.
C_0	No-load token circulation time.
M	Number of stations
$T\_Pri(j)$	Priority threshold value of asynchronous class j
b	Length of overhead bits added to each message
N_j	Number of messages transmitted by class j
λ_j	Arrival rate of messages of jth class/node
λ_j'	Modified arrival rate of messages of jth class/node
N	$= \sum_{j=0} N_j$, the total number of messages transmitted by the network during a token rotation
λ	Message arrival rate associated with N
L_{ij}	Length of the message i transmitted by class j.
L_i'	Length of message i when each class j has identical distributions.
L'	random variable having same distribution as L_i'
L_j	random variable having same distribution as L_{ij}
T_s	Time period during which synchronous message transmissions can be initiated after the token is received

Table 2: Notation-II

V_j	Vacation interval of class j
$\bar{V_j}$	First moment of the vacation interval of class j
$\bar{V_j^2}$	Second moment of the Vacation interval of class j
W_j	Mean waiting time of priority class j
$\bar{X_j}$	First moment of service time of class j
$\bar{X_j^2}$	Second moment of service time of class j
ρ_j	normalized utilization of class j/node
Z_j	Service time of class j
Y_j'	time to transmit all messages of class j at node 1 during rth and $(r+1)$th visit of the token
$\mathcal{E}[\,]$	Expected value of a random variable
$Var[\,]$	Variance of a random variable

transmission in the synchronous class is restricted by T_s. Hence, the service time of class 0 for any given network load can be written as:

$$Z_0 = Min[T_s \ , \ Y_0'] \ , \tag{3}$$

where Y_0' is the time to transmit all the messages of class 0 at node 1 during rth and (r+1)th visit of the token.

Figure 3 illustrates the messages transmitted by asynchronous class 1 during the rth and $r+1$th visit of the token. In this case however, the length of message transmission in class 1 is restricted by priority threshold $T\_Pri(1)$. The current value of the THT is equal to C_b. In Figure 3, C_i' is the token-cycle time measured from class 1 at node 1. Hence, the service time of class 1 for any given network load is given by:

$$Z_1 = Min[(T\_Pri(1) - C_b) \ , \ Y_1'] \ , \tag{4}$$

where Y_1' is the time to transmit all the messages of class 1 at node 1 during rth and (r+1)th visit of the token. When asynchronous class 2 receives the token, the current value of THT is $C_b + Z_1$. Therefore, the service time of this class can be written as:

$$Z_2 = Min[(T\_Pri(2) - C_b - Z_1) \ , \ Y_2'] \ , \tag{5}$$

where Y_2' is the time to transmit all the messages of class 2 at node 1 during rth and (r+1)th visit of the token. Similarly, the service time of asynchronous class 3 can be written as:

$$Z_3 = Min[(T\_Pri(3) - C_b - Z_1 - Z_2) \ , \ Y_3'] \ , \tag{6}$$

where Y_3' is the time to transmit all the messages of class 3 at node 1 during rth and (r+1)th visit of the token.

In the unsaturated region, the service time of each priority class can be approximated as (see [WeJB95]):

$$Z_j = Y_j' \ , \ for\ j = 0,1,2,3 \ . \tag{7}$$

The corresponding vacation intervals for each priority class can be written as:

$$V_j = C_j' - Y_i' \ , \ for\ j = 0,1,2,3 \ . \tag{8}$$

4.2 First and Second Moments of the Vacation Time

The Token-cycle time for a typical FDDI network with single synchronous class and three asynchronous classes can be written as follows [WeJB93];

$$C'_0 = C_0 + \sum_{i=1}^{N_0}(b + L_{i0}) + \sum_{i=1}^{N_1}(b + L_{i1}) + \sum_{i=1}^{N_2}(b + L_{i2}) + \sum_{i=1}^{N_3}(b + L_{i3}) . \quad (9)$$

Assuming symmetrical load distribution among all stations, the service time received by class 0 at a station can be approximated as:

$$Y'_0 = \frac{1}{M}\sum_{i=1}^{N_0}(b + L_{i0}) \quad (10)$$

Note that, the random variables L_{i0} and N_0 are the same for both Equations 9 and 10.

Case 1: *Message length distribution identical over classes*

By combining Equations 8, 9 and 10, an expression for the vacation time of class 0 can be written as:

$$V_0 = C_0 + \frac{M-1}{M}\sum_{i=1}^{N_0}(b + L_{i0}) + \sum_{j=1}^{3}\sum_{i=1}^{N_j}(b + L_{ij}) . \quad (11)$$

Using an analysis similar to that given in for token-cycle time in [WeJB93], the first moment and the variance of the vacation time seen by class 0 can be written as:

$$\mathcal{E}[V_0] = C_0 + (b + \mathcal{E}[L'])\Big\{\frac{M-1}{M}\mathcal{E}[N_0] + \mathcal{E}[N_1] + \mathcal{E}[N_2] + \mathcal{E}[N_3]\Big\} , \quad (12)$$

$$\begin{aligned} Var[V_0] &= b^2\Big(\Big(\frac{M-1}{M}\Big)^2 Var[N_0] + Var[N_1] + Var[N_2] + Var[N_3]\Big) \\ &+ \Big(\frac{M-1}{M}\Big)^2\Big\{\mathcal{E}[N_0]Var[L'] + \big(\mathcal{E}[L']\big)^2 Var[N_0]\Big\} \\ &+ \Big\{\mathcal{E}[\sum_{i=1}^{3} N_i]Var[L'] + \big(\mathcal{E}[L']\big)^2 Var[\sum_{i=1}^{3} N_i]\Big\} \\ &+ 2b\Big(\frac{M-1}{M}\Big)^2 Var[N_0]\mathcal{E}[L'] \\ &+ 2bVar[\sum_{i=1}^{3} N_i]\mathcal{E}[L'] . \end{aligned} \quad (13)$$

The derivation of Equations 12 and 13 are given in [Wera94]. The mean and the variance of the vacation time of class j $(0 \leq j \leq k)$ under these conditions are given by:

$$\mathcal{E}[V_j] = C_0 + (b + \mathcal{E}[L'])\Big\{\frac{M-1}{M}\mathcal{E}[N_j] + \sum_{i=0,i\neq j}^{k}\mathcal{E}[N_i]\Big\} , \quad (14)$$

$$\begin{aligned} Var[V_j] &= b^2\Big(\Big(\frac{M-1}{M}\Big)^2 Var[N_j] + \sum_{i=0,i\neq j}^{k} Var[N_i]\Big) \\ &+ \Big(\frac{M-1}{M}\Big)^2\Big\{\mathcal{E}[N_j]Var[L'] + \big(\mathcal{E}[L']\big)^2 Var[N_j]\Big\} \\ &+ \Big\{\mathcal{E}[\sum_{i=0,i\neq j}^{k} N_i]Var[L'] + \big(\mathcal{E}[L']\big)^2 Var[\sum_{i=0,i\neq j}^{k} N_i]\Big\} \\ &+ 2b\Big(\frac{M-1}{M}\Big)^2 Var[N_j]\mathcal{E}[L'] \\ &+ 2bVar[\sum_{i=0,i\neq j}^{k} N_i]\mathcal{E}[L'] . \end{aligned} \quad (15)$$

Case 2: *Message length distribution not identical over classes*

The first moment and the variance of the vacation time of class 0 can be evaluated using the Equation 11 as:

$$\mathcal{E}[V_0] = C_0 + b\Big\{\frac{M-1}{M}\mathcal{E}[N_0] + \mathcal{E}[N_1] + \mathcal{E}[N_2] + \mathcal{E}[N_3]\Big\} + \frac{M-1}{M}\mathcal{E}[N_0]\mathcal{E}[L_0] + \sum_{i=1}^{3}\mathcal{E}[N_i]\mathcal{E}[L_i] . \quad (16)$$

$$\begin{aligned} Var[V_0] &= b^2\Big(\Big(\frac{M-1}{M}\Big)^2 Var[N_0] + Var[N_1] + Var[N_2] + Var[N_3]\Big) \\ &+ \Big(\frac{M-1}{M}\Big)^2\Big\{\mathcal{E}[N_0]Var[L_0] \end{aligned}$$

$$
\begin{aligned}
&+ \quad \left(\mathcal{E}[L_0]\right)^2 Var[N_0]\Big\} \\
&+ \quad \sum_{i=1}^{3}\Big\{\mathcal{E}[N_i]Var[L_i] \\
&+ \quad \left(\mathcal{E}[L_i]\right)^2 Var[N_i]\Big\} \\
&+ \quad 2b\left(\frac{M-1}{M}\right)^2 Var[N_0]\mathcal{E}[L_0] \\
&+ \quad 2b\sum_{i=1}^{3} Var[N_i]\mathcal{E}[L_i] \ . \qquad (17)
\end{aligned}
$$

The derivation of Equations 16 and 17 are given in [Wera94]. The mean and the variance of the vacation time of class j $(0 \leq j \leq k)$ under these conditions are given by:

$$
\begin{aligned}
\mathcal{E}[V_j] \quad &= \quad C_0 \ + \ b\Big\{\frac{M-1}{M}\mathcal{E}[N_j] \ + \sum_{i=0,i\neq j}^{k} \mathcal{E}[N_i]\Big\} \\
&+ \quad \frac{M-1}{M}\mathcal{E}[N_j]\mathcal{E}[L_j] \\
&+ \quad \sum_{i=0,i\neq j}^{k} \mathcal{E}[N_i]\mathcal{E}[L_i] \ . \qquad (18)
\end{aligned}
$$

$$
\begin{aligned}
Var[V_j] \quad &= \quad b^2\Big(\left(\frac{M-1}{M}\right)^2 Var[N_j] \\
&+ \quad \sum_{i=0,i\neq j}^{k} Var[N_i]\Big) \\
&+ \quad \left(\frac{M-1}{M}\right)^2\Big\{\mathcal{E}[N_j]Var[L_j] \\
&+ \quad \left(\mathcal{E}[L_j]\right)^2 Var[N_j]\Big\} \\
&+ \quad \sum_{i=0,i\neq j}^{k}\Big\{\mathcal{E}[N_i]Var[L_i] \\
&+ \quad \left(\mathcal{E}[L_i]\right)^2 Var[N_i]\Big\} \\
&+ \quad 2b\left(\frac{M-1}{M}\right)^2 Var[N_j]\mathcal{E}[L_j] \\
&+ \quad 2b\sum_{i=0,i\neq j}^{k} Var[N_i]\mathcal{E}[L_i] \ . \qquad (19)
\end{aligned}
$$

5 Evaluation of Mean Waiting Time

The following steps are required in order to obtain the mean waiting time of the individual priority classes.

Step 1-Throughput characteristics: The throughput characteristics for the above FDDI network is obtained using the throughput model of [JaWe90]. Also use the same model to obtain the approximate values for the first moment of the token-cycle time.

Step 2- $\hat{\mathcal{E}}$[N],$\hat{\mathcal{E}}$[N$_j$],$\hat{Var}$[N] and $\hat{Var}$[N$_j$]: The estimates $\hat{\mathcal{E}}[N]$, $\hat{\mathcal{E}}[N_j]$, $\hat{Var}[N]$, and $\hat{Var}[N_j]$ for $j = 0, 1, 2, 3$ are evaluated using the iterative procedure given in [WeJB93, WeJB95] for the useful range of network offered load.

Step 3-$\mathcal{E}$[N$_j$] and Var[N$_j$]: Depending on the mean message length distribution, use the appropriate equations out of Equations 14, 15, 18 and 19 to estimate the mean and variance of the vacation intervals.

Step 4-Mean waiting time: For a given network offered load, find λ_j and ρ_j. Then substitute these values and first two moments of the vacation interval in Equation 1 to obtain the mean waiting time for the particular network offered load. Note that, λ_j and ρ_j in Equation 1 are the normalized values for a single station on the network.

6 Results

In this section, the analytical results obtained for the mean waiting time of individual priority classes using M/G/1 vacation model and corresponding simulation results are presented.

An FDDI network with 20 stations with each station having a synchronous class and three asynchronous classes is considered. The length of the fiber optic cable is 20 km. Message arrivals to each priority class are assumed to be Poisson and independent. The message length of each class is exponentially distributed with a mean of 2048 for asynchronous classes and a mean of 4096 for the synchronous class. Further, the priority threshold values of the individual priority classes $TTRT$ and T_s are selected such that, the condition $\hat{C}_0 > T\_Pri(1) > T\_Pri(2) > T\_Pri(3)$ is satisfied. Also, it is assumed that the traffic load in classes 0, 1, 2 and 3 is distributed to a ratio of 4:3:2:1. A summary of the network parameters are given in Table 3.

Figure 4 illustrates the throughput characteristics for the above FDDI network obtained using the throughput model of [JaWe90]. Figures 5, 6, 7 and 8 illustrate the mean waiting time of classes 3, 2, 1 and

Table 3: Network Parameters

M	20
L	20km
L'	4096 bits
T_s	85904 bits
$TTRT$	2500000 bits
$T\_Pri(1)$	1700000 bits
$T\_Pri(2)$	1400000 bits
$T\_Pri(3)$	1000000 bits

0 respectively obtained using M/G/1 vacation model. The simulation results are also given in the respective figures except for Figure 5. Simulation results for priority class 3 are not shown in Figure 5 due to the large simulation time required to get a statistically valid sample for this class at low load values. When the network offered load is very small ($\leq 10\%$), the mean waiting time is approximately equal to $\frac{C_0}{2}$. When the offered load is increased, asynchronous class 3 reaches saturation at 95% as shown in Figure 4. The simulations confirm this behavior. However, the analytical values are 10-15% higher than the simulations in the approximate neighborhood of 95% offered load. Asynchronous classes 2 and 1 shows similar behavior and these reach the saturation at 105% and 140% network offered loads respectively. Again, note that the analytical results are 10-15% higher than the simulations in the neighborhood of the saturation loads. However, the mean waiting time for synchronous class 0 in Figure 8 shows that the analytical results and the simulations are almost identical for the entire range of network offered load leading up saturation.

7 Summary

The analytical and simulation results show that the classical M/G/1 system with vacations provides a good estimates for the mean waiting time of individual priority classes of a homogeneous FDDI network. Above analysis is true if the condition $\hat{C}_0 > T\_Pri(1) > T\_Pri(2) > T\_Pri(3)$ is satisfied by the selected network parameters. However, it is possible to derive analytical expressions for the mean waiting time for cases such as $T\_Pri(1) > \hat{C}_0 > T\_Pri(2) > T\_Pri(3)$ or $T\_Pri(3) > T\_Pri(2) > T\_Pri(1) > \hat{C}_0$. The simulation results show that the mean waiting time estimates obtained from this model agree fairly closely for the entire region of network offered load considered. On contrary to the conclusions given in [LaSp90], this work has illustrated that M/G/1 vacation model can be used to evaluate the mean waiting time of all priority classes of homogeneous FDDI networks for the entire range of practical offered loads.

References

[AlJa94] B. Albert and A. P. Jayasumana, "FDDI and FDDI-II: Architecture, Protocols and Performance," Artech House Publishing, 1994.

[BeGa87] D. Bertsekas and R. Gallager, "Data Networks," Prentice-Hall, Inc., New Jersey, 1987.

[DyBu88] D. Dykeman and W. Bux, "Analysis and Timing of the FDDI Media Access Control Protocol," IEEE Selected Areas in Communications., Vol 6, No. 6, July 1988, pp 997-1010.

[GeVa90] W. L. Genter and K. S. Vastola, "Delay analysis of the FDDI Synchronous Data Class," Proceedings IEEE INFOCOM'90, June 1990, pp 766-773.

[GeVa89] W. L. Genter and K. S. Vastola, "Performance of The Token Bus for Time Critical Messages in a Manufacturing Environment," Proc. 1989 American Control Conf., June 1989.

[GuZR92] S. Gupta, M. E. Zarki and K. W. Ross, "Performance of FDDI Under Overload," Proc. of IEEE INFOCOM'92, pp 343-351.

[JaWe90] A. P. Jayasumana and P. Werahera, "Performance of Fibre Distributed Data Interface Network for Multiple Classes of Traffic," IEE Proc. , Vol. 137, Pt. E, No. 5, September 1990, pp 401-408.

[John87] M. J. Johnson, "Proof That Timing Requirements of FDDI Token Ring Protocol are Satisfied," IEEE Trans. Communications, Vol. 35, No. 6, June 1987, pp 620-625.

[KaLe92] D. Karvelas and A. Leon-Garcia, "Throughput and Delay Analysis of FDDI and FDDI-II under Mixed Traffic," IEEE Proc. of 17th Conf. on Local Computer Networks, Minneapolis, Minnesota, September, 1992, pp 142-151.

[KaLe88] D. Karvalas and A. Leon-Garcia, "Performance Analysis of the Medium Access Control Protocol of the FDDI Token Ring Network," Proc. of Globecom 1988, December, 1988, pp 1119-1123.

[Klei75] L. Kleinrock, "Queueing Systems, Volume 1: Theory," John Wiley & Sons, Inc., New York, 1975.

[Lama91] R. O. LaMaire, "An M/G/1 Vacation Model of an FDDI Station," IEEE J. on Selected Areas in Communications, Vol. 9, No. 2, February, 1991, pp 257-264.

[LaSp90] R. O. LaMaire and E. M. Spiegel, "FDDI Performance Analysis: Delay Approximations," Proc. of Globecom 1990, pp 1838-1845.

[Lee89] T. T. Lee, "M/G/1/N Queue with Vacation Time and Limited Service Discipline," Performance Evaluation, Vol. 9, June, 1989, pp 181-190.

[MAC87] "FDDI Token Ring Media Access Control (MAC)," Draft Proposed American National Standards, ANSI X3.139-1987.

[SeJo86] K. C. Sevick and M. J. Johnson, "Cycle Time Properties of The FDDI Token-Ring Protocol," IEEE T.A. of Software Engineering, Vol. SE-13, No. 3, March, 1987, pp 376-385.

[SMT89] "FDDI Station Management (SMT)," Draft Proposed American National Standards, Revision 5.1, September 1989.

[Taka90] H. Takagi, "Effects of the Target Token Rotation Time on the Performance of a Timed-Token Protocol," Performance'90, Elsevier Science Publishers (North Holland), 1990, pp 363-370.

[Tang91] M. Tangemann, "A Mean Value Analysis for Throughput and Waiting Times of the FDDI Timed Token Protocol," Proc. 13th International Teletraffic Congress, Copenhagen, Denmark, June 1991.

[TaSa91] M. Tangemann and K. Sauer, "Performance Analysis of the Timed Token Protocol of FDDI and FDDI-II," IEEE Selected Areas in Communications, Vol. 9, No. 2, February 1991, pp 271-278.

[WeJa94] P. Werahera and A. P. Jayasumana, "Fiber Distributed Data Interface: Throughput Evaluation with Multiple Classes of Traffic," IEEE Trans. Communications, Vol. 42, No. 2/3/4, February/March/April 1994, pp 499-510.

[WeJB93] P. Werahera, A. P. Jayasumana and D. C. Boes, "Token-Cycle Time Characteristics of FDDI Networks with Multiple Classes of Traffic," Proc. IEEE on Local Computer Networks, 1993, pp 503-512.

[Wera94] P. Werahera, "Performance Evaluation of FDDI Networks," Ph.D. Dissertation, Dept. of Electrical Engineering, Colorado State University, Fall 1994.

[WeJB95] P. Werahera, A. P. Jayasumana and D. C. Boes, "A Nonpreemptive Priority Delay Model with Modified-Vacation Intervals for Homogeneous FDDI Networks," Proc. of IEEE INFOCOM'95, pp 1282-1288.

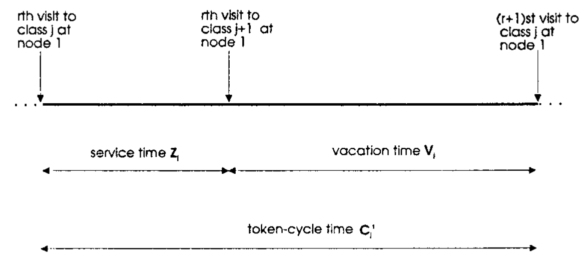

Figure 1: Relationship of token-cycle time, service time and vacation time

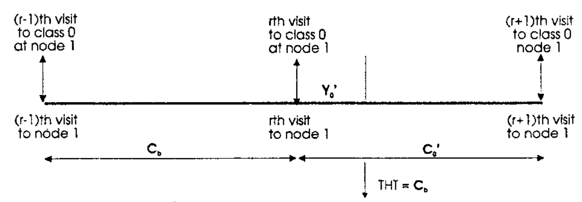

Figure 2: Service time received by class 0 at node 1

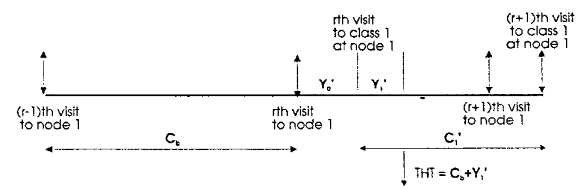

Figure 3: Service time received by class 1 at node 1

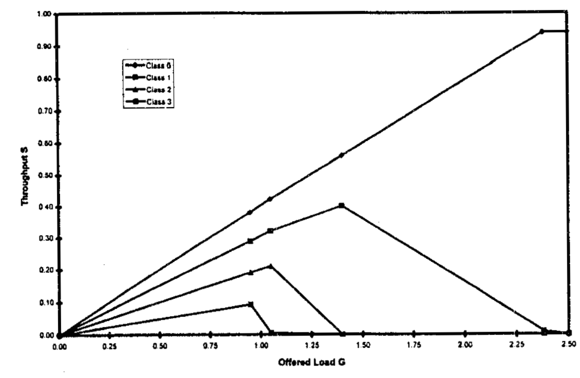

Figure 4: Throughput characteristics for the FDDI network

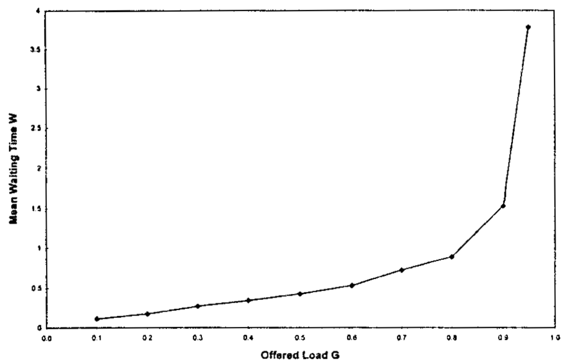

Figure 5: Mean waiting time of class 3 traffic vs network offered load

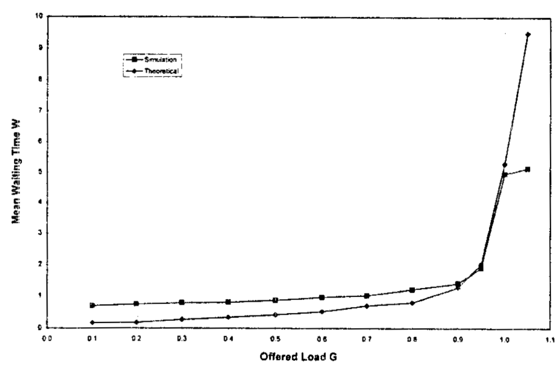

Figure 6: Mean waiting time of class 2 traffic vs network offered load

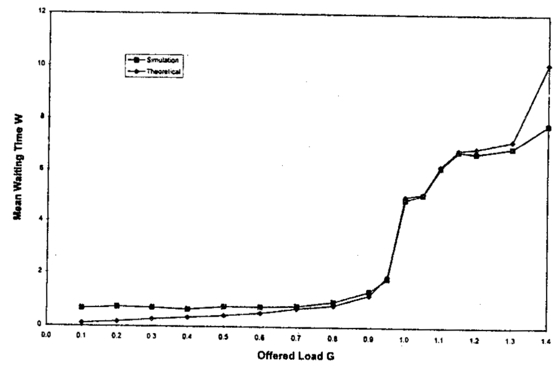

Figure 7: Mean waiting time of class 1 traffic vs network offered load

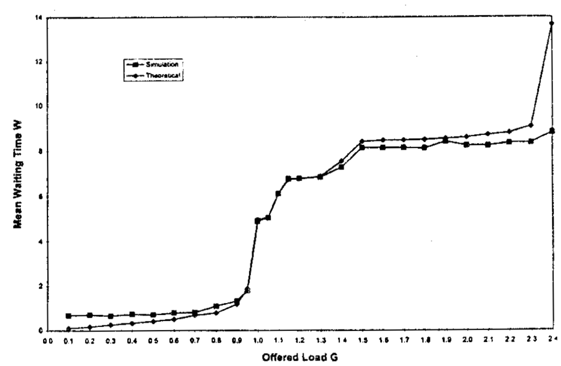

Figure 8: Mean waiting time of class 0 traffic vs network offered load