Effectiveness of the FDDI-M Protocol in Supporting Synchronous Traffic

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Abstract

Timed token networks such as FDDI networks has been widely deployed to support synchronous traffic. However the medium access control (MAC) protocol of FDDI allows transmission of synchronous messages up to at most one half of the total bandwidth of the network. Shin and Zheng has proposed a modification to the FDDI MAC protocol, called FDDI-M, which can double a ring's ability in supporting synchronous traffic (Shin and Zheng, 1995). It is widely known that the ability of timed token protocols such as FDDI to guarantee synchronous message deadlines is very dependent on the synchronous bandwidth allocation (SBA) schemes used, but the original paper does not address this issue. In this paper, we will compare the ability of FDDI-M to support synchronous traffic under different SBA schemes with that of FDDI. We use a new taxonomy of SBA schemes based on the strategy used to partition the synchronous bandwidth, and present an analytical study of the timing properties of the FDDI-M protocol using the Worst Case Achievable Utilization (WCAU) as the performance metric. The results show that while FDDI-M improves the WCAU values under one class of SBA schemes, its performance under the other category of SBA schemes is mixed. We also perform extensive simulation to study performance of FDDI-M for MPEG video traffic, and conclude FDDI-M does outperform FDDI significantly at heavy load. The effect of SBA schemes under overload conditions is also shown to be relatively minor, with the local SBA schemes actually performing better than the global schemes.

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1. Introduction

The Fiber Distributed Data Interface (FDDI) is a high-speed, fiber-optic token ring network proposed in the late 1980s. Since then it has seen wide usage, primarily as backbone for interconnecting local speed LANs. FDDI can provide bounded transmission delays and guaranteed bandwidth for real-time traffic. Messages are grouped into two classes: synchronous and asynchronous. Synchronous messages are used primarily for real-time communication; they arrive in the system at regular intervals and may be associated with deadline constraints. This class of messages is especially suitable for *continuous* media communications such as audio and video transmission. Asynchronous messages are used for *non-continuous* communications such as file and fax transfer; they may arrive in a random way and have no hard real-time constraints. The basic strategy of the FDDI MAC ensures that every station in the network is guaranteed a certain average bandwidth for its synchronous traffic, with the remaining bandwidth dynamically shared by all stations for asynchronous traffic. FDDI networks have been widely deployed in both academic and commercial environments and its performance a topic of much research activities.

Of much interest to researchers is the FDDI MAC protocol, which is an example of the timed token protocol (Grow, 1992) in which access to the communication medium is controlled by a token that is passed among the stations. Besides giving each station a guaranteed share of the network bandwidth, it has the important property of bounding time between any two consecutive visits of the token to a node. Unfortunately, since the worst case token rotation time is twice that of the average token rotation time, only at most one half of the bandwidth of a FDDI ring can be used to transmit synchronous messages (Grow, 1992).

In a recent paper, Shin and Zheng proposed a modification to the FDDI MAC protocol, called FDDI-M. It is shown through simulations that FDDI-M doubles a ring’s ability of supporting synchronous traffic while at the same time achieves a higher throughput for asynchronous traffic than the standard FDDI. However, in the original paper, there is no formal analysis of the timing properties of the FDDI-M protocol with respect to various SBA schemes. On the other hand, the ability of FDDI to support synchronous traffic has been determined for many different SBA schemes using *Worst Case Achievable Utilization* (WCAU) as the performance metric (see section 2 for a more detailed discussion). The WCAU of a SBA scheme is defined as the largest utilization U such that the scheme can always guarantee the deadlines of a synchronous message set as long as the utilization of the message set does not exceed U. This metric is derived from the equivalent metric used for scheduling tasks in real-time systems (Liu and Layland, 1973) and is frequently used because it simplifies system configuration considerably by eliminating the need to

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deal with individual values of synchronous and asynchronous message length, inter-arrival periods and so on. As long as the total utilization of the synchronous messages is no more than the WCAU of the protocol, the message set is guaranteed to meet the deadlines.

Many SBA schemes have been proposed in the literature, and it can be very tedious to derive the performance of FDDI-M under each of these schemes and compare with FDDI to see if there are improvements in each case. In this paper we first analyze the many different SBA schemes proposed in the literature, and then divide them into two classes based on how the bandwidth is allocated. This allows us to focus on a particular class of SBA schemes and study their behaviour. We then proceed to compare the performance of FDDI-M using WCAU for each of the two classes of SBA schemes. As we will see, the result is mixed, with improvement in some cases, and no improvement in others. In some other cases, the WCAU may actually decrease when FDDI-M is used

While WCAU is a useful and objective metric, there are many practical network scenarios where the network is heavily loaded (or even overloaded) and it is acceptable to have a small percentage of synchronous messages miss their deadlines. One such example is video traffic, where frame miss rate is perhaps the most important metric, particularly when the network is heavily loaded. Thus, to complete our study, we use a set of realistic network scenarios involving MPEG video traffic similar to those used in (Shin and Zheng, 1995) to further evaluate the effectiveness of FDDI-M under different SBA schemes. We conclude that FDDI-M *does* significantly improve synchronous bandwidth allocation when compared to FDDI, and that this improvement is relatively independent of the SBA schemes.

The rest of the paper is organized as follows. Section 2 briefly describes the FDDI and FDDI-M protocols and reviews related work on the timing properties of the FDDI and FDDI-M protocols. In Section 3, we present a classification of SBA schemes based on their approaches in allocation synchronous bandwidth. In Section 4 we compare the performance of FDDI-M with FDDI for both classes of SBA schemes using WCAU. In Section 5, we study the performance of FDDI-M under different SBA schemes using simulation for MPEG video traffic. The paper concludes with Section 6.

2. Overview of FDDI and FDDI-M

We first review the basic operation of the FDDI MAC protocol. First of all, we note that two network parameters are particularly important for the operation of the protocol:

Target Token Rotation Time (*TTRT*): the expected time for the token to make one rotation through all the stations in the network.

The *Synchronous Bandwidth* (H_i) of each station: the time guaranteed for transmitting synchronous message every time the station receives the token.

During the initialization of the ring, all the stations negotiate a common value for *TTRT*. In addition, each station is allocated its synchronous bandwidth according to a predetermined scheme (the SBA scheme). Besides these two constants, each station maintains two local timers, the *Token Holding Timer* (*THT*) and the *Token Rotation Timer* (*TRT*), and a flag, the *Late Count* (*LC*). *THT* is the residual time from synchronous transmission for asynchronous packets and *TRT* is used to monitor how much earlier the token arrives. *TRT* always counts up and *THT* counts up only when transmitting asynchronous messages. If *TRT* reaches *TTRT* before the token arrives (i.e. the time since the token was last received at the same station is greater than *TTRT*), it is reset to 0 and *LC* is incremented.

When a station captures the token and wants to transmit a message, it first copies its *TRT* to *THT* and then resets *TRT* to 0. It then transmits the synchronous traffic up to H_i unit of time or until no synchronous packets are enqueued, whichever comes earlier. After synchronous messages have been transmitted, asynchronous messages are transmitted only if the token arrived at the station earlier than expected (*LC* = 0). If this is the case, *THT* will start counting down and asynchronous transmission will end when there are no asynchronous packets enqueued or *THT* has expired. Note that, the asynchronous traffic may increase the actual token rotation time beyond *TTRT* because if a maximum size asynchronous packet is transmitted right before the *THT* expires, the asynchronous transmission time will exceed *THT*.

The possibility of asynchronous packets overrun affects the schedulability of synchronous messages. As proved in (Johnson 1987), the extra time consumed by accumulated overrun packets result in a token round-trip rotation delay of 2*TTRT*. This means that the worst-case delay bound *D* for inter-token arrival time is also 2*TTRT*. Thus, if the deadline requirement of a station's synchronous traffic has delay bound *D*, then the *TTRT* must be set to have a value no greater than *D*/2 in order to ensure the deadline requirement of the synchronous packets is met. Consequently, the total allocated synchronous bandwidth T_S in one rotation of the token is bounded by $D/2 - T_{ring}$, where, T_{ring} is the token passing overhead. Since the actual usable synchronous bandwidth of a ring is $D - T_{ring}$, the FDDI MAC protocol essentially halves the capability of FDDI in supporting synchronous transmission. In other words, due to the inherent deficiency in the FDDI MAC protocol, only at most one half of the bandwidth of a FDDI ring can be used to transmit synchronous messages.

We will now discuss briefly how the FDDI-M scheme differs from FDDI. Suppose T_p is the time to transmit a maximum size asynchronous packet. FDDI-M first redefines the modified rotation timer ($TTRT_m$) to be $TTRT - T_S - T_p$ instead of $TTRT$. Next, it stops the node's TRT when a synchronous packet is being transmitted/forwarded by the node. $TTRT_m$ will cater for the time for a maximum size asynchronous packet overrun and the modified way of TRT counting will only count the asynchronous transmission time. With these modifications, the THT at each node ensures that T_A, the time used by the node for asynchronous transmission, will not exceed $TTRT_m - T_p - T_{ring} = TTRT - T_S - T_{ring}$. Since $T_S = TTRT - T_{ring}$, the maximum token rotation time will be $T_A + T_S + T_{ring} = TTRT$. Thus, the worst-case delay bound for inter-token arrival time is $TTRT$. In essence, FDDI-M limits the total time used for asynchronous messages of all nodes such that it is not possible to have a late token. Hence the worst case token rotation is the same as that of the average token rotation time, thus improving the ability of the token ring to handle synchronous traffic.

The timing properties of the FDDI protocol have been extensively studied. Johnson and Sevcik formally proved that when the network operates normally, the upper bound on the token rotation time is twice the expected token rotation time, i.e., $2*TTRT$ (Johnson and Sevcik, 1987). The difference between the maximum token rotation time and the achievable average token rotation time halves an FDDI token ring's ability of transmitting synchronous traffic, and it is this deficiency in FDDI's protocol that motivated the proposal of FDDI-M.

To guarantee the transmission of synchronous messages before their deadlines, it is important to select the appropriate values for the parameters $TTRT$ and H_i. Various schemes for allocating synchronous bandwidth of each station have been proposed in the literature. Agrawal et al, first proposed and analyzed a number of SBA schemes (Agrawal, Chen and Zhao, 1992). They showed that the WCAU of two local SBA schemes (the *full length allocation scheme* (FLA) and the *proportional allocation scheme* (PA)) can asymptotically approach 0%. Two other schemes, *the equal partition allocation scheme* (EPA) and the *normalized proportional allocation scheme* (NPA), fare better, with the latter achieving a WCAU of 33% if the value of $TTRT$ is selected as recommended in the FDDI standard (Agrawal et al, 1994). However, this SBA scheme is a *global* one, in that system wide information such as message periods and lengths on the nodes as well as the total utilization is required. As a result, global SBA schemes are not very suitable for dynamic environments since changes in the message stream at a particular node may cause the synchronous bandwidth allocation for all other nodes to be recalculated. On the other hand, the local SBA schemes have zero WCAU, which is not very satisfactory. Not surprising, researchers have striven since then to find SBA schemes with higher WCAU.

Agrawal et. al. also proposed a new local SBA scheme (LA) which performs substantially better than their predecessors (Agrawal, Chena and Zhao, 1993). This scheme can achieve a WCAU of 33% for message sets with message periods equal to deadlines. In another paper, Malcolm and Zhao generalized Agrawal's scheme by allowing each message to have an arbitrary deadline (Malcolm and Zaho, 1993). Zhang recently proposed modifications to the LA scheme, called the *improved local allocation scheme* (ILA), which explicitly takes into account synchronous bandwidth allocation for synchronous message sets with minimum message deadline less than 2**TTRT* (Zhang 1993). Another scheme called the *exhaustive local allocation* scheme (ELA) was later proposed which is claimed to outperform all of the schemes previously proposed in the literature [Zhang and Burns, 1996].

An allocation scheme is optimal if it can always guarantee a message set whenever there exists an allocation that can do so. While local SBA schemes are simple to implement and of great practical interest, it has been proved that no local SBA schemes are optimal (Han, Shin and Hou, 1995). An optimal global SBA scheme, called *the minimum capacity allocation scheme* (MCA), was first proposed in (Chen, Agrawal and Zhao, 1992). However, it was pointed out that besides being restricted to the case where the minimum message deadline is greater than or equal to 2**TTRT*, MCA does not always generate the optimal allocation. An enhanced version of MCA, called the *enhanced minimum capacity allocation scheme* (EMCA), was proposed to address these problems and the scheme was claimed to be optimal (Zhang 1996). Recently, an upper bound on WCAU for any SBA scheme was derived (Hamdaoui and Ramanathan, 1995), where an algorithm for choosing the value of *TTRT* was also given.

The FDDI-M MAC protocol, despite its potential, has not been studied extensively in the literature. Leung proposed a scheme to further optimize FDDI-M by using unused portion of synchronous bandwidth to transmit asynchronous packets, a scheme known as FDDI-M* (Leung, 1994). Note this scheme does not attempt to improve the ability of FDDI-M in supporting synchronous traffic. In a previous paper (Chan et al, 1997), we have derived analytically the WCAU values for three of the earliest SBA schemes proposed in (Agrawal, Chen and Zhao, 1992). Some simulation work on the ability of FDDI-M to support video traffic has also appeared previously (Tsang et al, 1995), but the results are based only on the FLA SBA scheme.

3. Taxonomy of the SBA Schemes

SBA schemes are generally classified into local or global schemes according to whether they need global state information or not. In this section, we explain how this classification can be extended by examining the way SBA schemes partition the bandwidth, and also demonstrate the form in which these SBA schemes must take in order to maximize the WCAU (Chen, Chan and Lee, 1998). This classification is useful because it allows us to compare FDDI and FDDI-M for each category of SBA schemes instead of every individual scheme.

We first describe the characteristics of the synchronous messages in our model. This model is the same as that used in [4] and is widely used in the study of FDDI and its associated SBA schemes:

1. Synchronous messages are *periodic,* i.e., messages in a synchronous message stream have a constant inter-arrival time. We denote P_i to be the period length of stream S_i (i = 1, 2, … ,n).
2. The *deadline* of a synchronous message is the end of the period in which it arrives. That is, if a message in stream S_i arrives at time t, then its deadline is at time $t+P_i$.
3. Messages are independent in that message arrivals do not depend on the initiation or the completion of transmission requests for other messages.
4. The *length* of each message in stream S is C which is the maximum amount of time needed to transmit this message.

Any SBA scheme must satisfy two basic constraints (Johnson, 1987; Agrawal, Chen and Zhao, 1992):

1. Protocol constraint: the sum of the synchronous capacities allocated to all nodes in the FDDI ring should not be greater than the available portion of *TTRT* i.e.

$$\sum_{i=1}^{n} H_i \le TTRT - t$$

2. Deadline constraint: the allocation of the synchronous capacities to the nodes must guarantee that the synchronous messages are always transmitted before their deadlines i.e., before the end of the period in which they arrived. This means that if X_i is the minimum time available for node i to transmit its synchronous message in the time interval (t, $t+P_i$) then

$$X_i \ge C_i .$$

Although there are many different SBA schemes, we can divide them into two categories according to the way they attempt to achieve an optimal bandwidth allocation. The first approach attempts to divide the expected time for the token to make one rotation (i.e. *TTRT-t*) among all the message streams. There are at least two SBA schemes which use this approach: EPA and NPA. For this class of SBA schemes, the protocol constraint is always satisfied since the basic strategy of the scheme is the same as that of the protocol constraint itself. This assumes of course that some fundamental network requirements, such as the total synchronous loading rate is no more than 1-α (where $a = \frac{t}{TTRT}$) are satisfied.

The second approach is for the SBA scheme to partition the time length required to send a message, C_i, for each synchronous message stream among a certain number of token rotating cycles. An example for this approach is the LA scheme ($H_i = \frac{C_i}{\left\lfloor \frac{P_i}{TTRT} \right\rfloor - 1}$) [5].

It has been proved in (Chen, Agrawal and Zhao, 1992) that, assuming at time t a synchronous message with deadline D_i arrives at node $i(1 \le i \le n)$, then with $P_i = D_i$, in time interval $(t, t+D_i]$ the minimum amount of time X_i available for node i to transmit its synchronous messages is given by:

$$X_i = (q_i - 1) \cdot H_i + \max\left\{0, \min\left[r_i - \left(\sum_{h=1,\ldots,n\ h \ne i} H_h + t\right), H_i\right]\right\} \qquad (1)$$

where $q_i = \left\lfloor \frac{P_i}{TTRT} \right\rfloor$ and $r_i = D_i - q_i \cdot TTRT$.

So, if we partition the time length of C_i's among no more than $\left\lfloor \frac{P_i}{TTRT} \right\rfloor - 1$ token rotation cycles, then the deadline constraint can always be satisfied for any set of synchronous message streams.

We have proposed in a previous paper to call the two classes of SBA schemes *TTRT-partitioning* and *C_i-partitioning* schemes respectively (Chen, Chan and Lee, 1998). These two classes of schemes represent the two intuitive approaches for tackling the bandwidth allocation problem given the two basic constraints of any SBA scheme. *TTRT*-partitioning schemes always satisfy the protocol constraint, and attempts to maximize the WCAU subject to the deadline constraint. C_i-partitioning schemes, on the other hand, will always satisfy the deadline constraint subject to certain additional conditions, and then attempts to maximize the WCAU subject to the protocol constraint. In fact we can see that the strategy that should be taken by all C_i-partitioning schemes to maximize the WCAU is to partition the length of C_i's among as large number of token rotation cycles as possible, with upper bound to satisfy the deadline constraint. This can be proved by the following theorem.

Theorem 1

For any set of synchronous message stream M, when using two different C_i-partitioning schemes S_1 and S_2, with each C_i evenly partitioned among k_1 and k_2 token rotation cycles, respectively, if both k_1 and k_2 are selected as to guarantee the deadline constraint as discussed above, and $k_1 \ge k_2$, then if M can be guaranteed by S_2, it can be guaranteed by S_1 as well.

Corollary 1

As far as the WCAU is concerned, when selecting a C_i-partitioning SBA scheme, we should partition the length of C_i's among as large number of token rotation cycles as possible, with upper bound to satisfy the deadline constraint.

The proof of the above theorem is given in (Chan, Chen and Lee, 1998).

Next we examine the form of C_i-partitioning schemes. A class of C_i-partitioning schemes was introduced in (Agrawal, Chen and Zhao, 1992):

$$H_i = \frac{C_i}{a.\frac{P_i}{TTRT} + b} \qquad (2)$$

in which, $0 \le a \le 1$ and b is selected appropriately to guarantee the deadline constraint.

Actually, if our goal is to maximize the WCAU in a C_i-partitioning scheme, then forms other than (2) above are meaningless. This can be justified in two ways. From a technical point of view, partitioning a length of C_i among non-uniform token cycles is not practical. Mathematically, it is easy to see that uneven partitioning can only decrease the value of the WCAU, since it is easy to design a set of synchronous message stream with a specific set P_i's to make the sum of the synchronous bandwidth within a specific token cycle larger than normal sum of H_i's in an even partitioning.

Note that if a=0 then the scheme turn out to FLA, which has a WCAU of zero. It is interesting to note that with the exception of this special case, all schemes of the form described by (2) above has been proved to have a non-zero WCAU (Agrawal, Chen and Zhao, 1992).

	TTRT-partitioning	C_i-partitioning
Local Scheme	PA	FLA LA ILA ELA
Global Scheme	EPA NPA	MCA EMCA

Table 1 Classification of SBA Schemes

Table 1 shows that we can classify the SBA schemes proposed in the literature according to whether they are local or global, and C_i-partitioning or *TTRT*-partitioning. Use this classification can be quite useful in comparing the performance of FDDI and FDDI-M, as we will see in the following sections.

4. WCAU for FDDI-M under Different SBA Schemes

Having classified SBA schemes into two types, we now proceed to examine their WCAU values to see if we can generalize about the behaviour of FDDI-M for each type of SBA schemes.

4.1 WCAU for *TTRT*-partitioning SBA Schemes

The WCAU for the *TTRT*-partitioning SBA schemes for both FDDI and FDDI-M have been derived elsewhere [Agrawal, Chen and Zhao, 1992; Chan et al, 1997; Chen Chan and Lee, 1998); we summarize them in Table 1. The PA scheme is a local scheme whereas the NPA and EPA schemes are both global schemes.

	FDDI	FDDI-M
PA	0	0
EPA	$\frac{1-a}{3n-(1-a)}$	$\frac{1-a}{2n-(1-a)}$
NPA	$\frac{1-a}{3}$	$\frac{1-a}{2}$

Table 1 WCAU of *TTRT*-partitioning SBA schemes under FDDI and FDDI-M

It is interesting to note that no local *TTRT*-partitioning SBA scheme with a non-zero WCAU has been reported in the literature. From Table 1, it can be seen that the global SBA schemes have their WCAU increased by about 50% for NPA and the same amount for EPA when n is large. The original design objective of FDDI-M is to double the ring's capacity to transmit synchronous traffic. We see that for the *TTRT*-partitioning SBA schemes the result is somewhat less promising when WCAU is used as the performance metric. On the other hand, no known SBA schemes under FDDI has a WCAU that is greater than 33%. Thus, FDDI-M has not only increased the WCAU of the global *TTRT*-partitioning SBA schemes but also effectively raised the best achievable values under FDDI.

4.2 WCAU for C_i -partitioning SBA schemes

We have seen in the Section 2 that C_i-partitioning SBA schemes in general have the form described in (2). In this section we will examine some representative schemes in this category and demonstrate that FDDI-M does not always improve WCAU. The approach we will take is as follows. First we deal with some special cases. This includes schemes that cannot be compared directly under FDDI and FDDI-M. Next we select a representative SBA scheme, the ILA scheme, and examine whether FDDI-M offer any improvement in scheduling synchronous traffic. The ILA scheme is chosen because it places little restriction on the minimum period of the messages. We will show that the effect of FDDI-M is quite mixed and depends on the composition of the traffic, and we will demonstrate conditions for which performance of FDDI-M actually is worse than FDDI. The result is not restricted to ILA but can be applied to other C_i-partitioning SBA schemes as well. Finally, we illustrate some special cases where using FDDI-M can in fact be used to achieve the maximum possible WCAU.

We will first consider the FLA scheme, which is a special case of (2) with a=0 and b=1. It has been proved that the WCAU of FLA is zero under both FDDI (Agrawal, Chen and Zhao, 1992) and FDDI-M (Chan et al, 1997).

Next we consider the LA scheme. The LA scheme is defined as follows:

$$H_i = \frac{C_i}{\left\lfloor \frac{P_i}{TTRT} \right\rfloor - 1}$$

Unfortunately, this scheme cannot be used for FDDI-M, since for the node *i* with minimum period which is equal to *TTRT*, the denominator will be zero. However, for FDDI-M, we have (Chan et al, 1997):

$$X_i = \left\lfloor \frac{P_i}{TTRT} \right\rfloor \cdot H_i + \Delta_i$$

where, if $d_i = \lceil P_i / TTRT \rceil \cdot TTRT - P_i = 0$, then $D_i = 0$, otherwise $D_i = \max(0, H_i - d_i)$. ($\lceil x \rceil$ denotes the smallest integer not smaller than x.)

Comparing this equation about X_i to equation (1), we can change the LA scheme for FDDI-M as follows:

$$H_i = \frac{C_i}{\left\lfloor \frac{P_i}{TTRT} \right\rfloor} \qquad (3)$$

We call this the *modified LA scheme* (MLA) and note this scheme can always satisfy the deadline constraint of any synchronous message streams using FDDI-M. Hence, the WCAU will depend solely on how the protocol constraint is to be met, like all other C_i-partitioning SBA schemes. Unfortunately this MLA scheme cannot satisfy the deadline constraint for FDDI, since only $\left\lfloor \frac{P_i}{TTRT} \right\rfloor - 1$ arrivals of the token are guaranteed during the time of $(t, t+P_i)$. So, no direct comparison can be given for LA or even the MLA scheme.

Now we consider the ILA scheme, which can be used for both FDDI and FDDI-M. The ILA scheme is defined as follows:

$$H_i = \frac{C_i}{\max\left(\left\lfloor \frac{P_i}{TTRT} \right\rfloor - 1, 1 \right)}$$

Given a specific set of synchronous message stream with the minimum period $P_{\min}$, when using FDDI, we have $TTRT = \dfrac{P_{\min}}{2}$, and, $H_i = \dfrac{C_i}{\dfrac{2P_i}{P_{\min}} - 1}$ for all i, and when using FDDI-M, we have $TTRT^M = P_{\min}$,

and, $H_i^M = \dfrac{C_i}{\left\lfloor \dfrac{P_i}{P_{\min}} \right\rfloor - 1}$ for all i with $P_i \geq 2 \cdot P_{min}$ and $H_i^M = C_i$ for all other i .

The following can be proved readily:

(i) for all P_i with $P_{min} \leq P_i < 1.5P_{min}$, $H_i = H_i^M = C_i$;

(ii) for all P_i with $1.5P_{min} \leq P_i < 2P_{min}$, $2 \cdot H_i = H_i^M$

(iii) for all $P_i \geq 2 \cdot P_{min}$, $2 \cdot H_i = \dfrac{2C_i}{\left\lfloor \dfrac{2P_i}{P_{\min}} - 1 \right\rfloor} < \dfrac{C_i}{\left\lfloor \dfrac{P_i}{P_{\min}} - 1 \right\rfloor} = H_i^M$

which leads to the following result.

Theorem 2

For any set of synchronous message stream M, assume that $(H_1, H_2, ..., H_n)$ and $(H_1^M, H_2^M, ..., H_n^M)$ are synchronous bandwidth allocation vectors using ILA scheme under FDDI and FDDI-M, respectively, then we have:

$$\sum_{i=1}^{n} H_i{}^M \geq 2 \cdot \sum_{i=1}^{n} H_i$$

as long as the following inequality is satisfied:

$$\sum\nolimits_1 H_i + t \leq \Delta_1 + \Delta_2 \qquad (4)$$

where: $\sum_1 H_i = \sum_i H_i$ for all i satisfying $P_{\min} \leq P_i \leq 1.5P_{\min}$,

$$\Delta_1 = \sum_i \frac{C_i}{(k_i - 1) \cdot (2k_i - 1)} \text{ for all } i \text{ satisfying } k_i = \left\lfloor \frac{P}{P_{\min}} \right\rfloor \geq 2 \text{ and } 0 \leq \frac{P_i}{P_{\min}} - \left\lfloor \frac{P_i}{P_{\min}} \right\rfloor < \frac{1}{2},$$

$$\Delta_2 = \sum_i \frac{C_i}{k_i \cdot (k_i - 1)} \text{ for all } i \text{ satisfying } k_i = \left\lfloor \frac{P}{P_{\min}} \right\rfloor \geq 2 \text{ and } \frac{1}{2} \leq \frac{P_i}{P_{\min}} - \left\lfloor \frac{P_i}{P_{\min}} \right\rfloor < 1$$

Proof:

Let $M = (M_1, M_2, ..., M_n)$ be any set of synchronous message streams. Each M_i has message length C_i and period P_i . Let P_{min} be the minimum period.

For the ILA scheme, we have for FDDI (with $TTRT$ selected as $\frac{1}{2} \cdot P_{min}$):

$$H_i = \frac{C_i}{\left\lfloor \frac{P_i}{TTRT} - 1 \right\rfloor} = \frac{C_i}{\left\lfloor \frac{2P_i}{P_{\min}} - 1 \right\rfloor}$$

and for FDDI-M (with $TTRT$ selected as P_{min}):

$$H_i^M = C_i \text{ when } P_i<2\cdot TTRT \text{ and } H_i^M = \frac{C_i}{\left\lfloor \frac{P_i}{P_{\min}} - 1 \right\rfloor} \text{ when } P_i\geq 2\cdot TTRT$$

.

According to the values of P_i's, we can assign each M_i to one of four types (H_i and H_i^M are allocated synchronous bandwidth under FDDI and FDDI-M respectively, using ILA):

Type 1: $P_i = (1+ a)\cdot P_{min}$, where $0\leq a<0.5$. For type 1 messages:

$$H_i = H_i^M = C_i .$$

Type 2: $P_i = (1+ a)\cdot P_{min}$, where $0.5\leq a<1$. For type 2 messages:

$$H_i^M = C_i = 2\cdot \frac{1}{2} \cdot C_i = 2\cdot H_i .$$

Type 3: $P_i = (k_i+ a)\cdot P_{min}$, where k_i is an integer no less than 2, and $0\leq a<0.5$. For type 3 messages:

$$H_i^M = \frac{C_i}{k_i - 1} = \frac{2 \cdot C_i}{2k_i - 1} + d_i = 2\cdot H_i + d_i$$

where $d_i = \dfrac{C_i}{(k_i - 1)\cdot(2k_i - 1)} > 0$, so, $H_i^M > 2\cdot H_i$.

Type 4: $P_i = (k_i+ a)\cdot P_{min}$, where k_i is an integer no less than 2, and $0.5\leq a<1$. For type 4 messages:

$$H_i^M = \frac{C_i}{k_i - 1} = \frac{2 \cdot C_i}{2k_i} + e_i = 2\cdot H_i + e_i$$

where $e_i = \dfrac{C_i}{k_i \cdot (k_i - 1)} > 0$, so, $H_i^M > 2\cdot H_i$.

Now, if the protocol constraint of M cannot be satisfied under FDDI, the following must hold:

$$\sum_{i=1}^{n} H_i > TTRT - t$$

We rewrite this as:

$$S_1 + S_2 + S_3 + S_4 > TTRT - t$$

where S_i is the sum of H_k's in type i . Multiplying both sides of the inequality by 2, we get:

$$2S_1 + 2S_2 + 2S_3 + 2S_4 > 2TTRT - 2t$$

Note that: $2S_1 = S_1{}^M + S_1{}^M$, $2S_2 = 2S_2{}^M$, $2S_3 = 2S_3{}^M - \Delta_1$ and $2S_4 = 2S_4{}^M - \Delta_2$, where S_i^M is the sum of H_k^M's in type i and Δ_1, Δ_2 are sums of all d_i's, e_i's, respectively, so:

$$(S_1{}^M + S_2{}^M + S_3{}^M + S_4{}^M) + (S_1{}^M + \tau - \Delta_1 - \Delta_2) > 2TTRT\text{-}t = TTRT^M - \tau$$

So for the ILA scheme for any set of synchronous message streams for which P_i's and C_i's satisfy $S_1{}^M + \tau \le \Delta_1 + \Delta_2$, if its protocol constraint cannot be satisfied under FDDI, then it cannot be satisfied under FDDI-M as well.

By Theorem 2, it is easy to see that, for any set of synchronous message streams with a set of P_i's of appropriate values, $\sum_{i=1}^{n} H_i{}^M > TTRT^M - t$ can be readily derived from the inequality $\sum_{i=1}^{n} H_i > TTRT - t = \frac{1}{2} \cdot TTRT^M - t$, which means that, for a synchronous message stream satisfying the conditions above, if the protocol constraint cannot be satisfied under FDDI, then nor can it be satisfied under FDDI-M. Since the deadline constraint can always be satisfied, it can be concluded that if it cannot be guaranteed under FDDI, it cannot be guaranteed under FDDI-M. In other words, FDDI-M does not offer any improvement over FDDI in terms of supporting synchronous traffic streams.

Unfortunately, it is not hard to construct a set of synchronous message stream satisfying the conditions required by Theorem 2. In fact, since the value of τ in equation (4) is typically small, unless the values of a considerable number of P_i's are within the range of $[P_{\min}, 1.5P_{\min})$, it is not hard to construct a set of synchronous message stream that cannot be guaranteed under FDDI-M, even though it can be guaranteed under FDDI.

We will now briefly discuss why the above results apply to the other C_i-partitioning SBA schemes. We first make the observation that the schemes which have better performance than the ILA scheme are based on obtaining a tighter upper bound on X_i for equation (1). This include schemes such as ELA and EMCA. Next we note that most of the improvement are essentially squeezed from the last incomplete token rotation cycle within the time interval of $[t, t+P_i]$ for any i. Since the key modification in the FDDI-M protocol is that it limits the total time used for asynchronous messages of all nodes such that it is not possible to have a late token, optimizing performance on the last incomplete token rotation cycle will have the same effect on both FDDI and FDDI-M. Based on this reasoning, the results we obtain the ILA scheme can be applied to other known C_i-partitioning SBA schemes as well.

We should perhaps point out that FDDI-M is not always inferior to FDDI. There are some special cases in which FDDI-M can result in higher a WCAU. In addition we note that the SBA schemes proposed in the literature are designed originally for FDDI and that no SBA schemes has been designed specifically for FDDI-M. It is possible to construct FDDI-M specific SBA schemes that have higher WCAU values. As a simple illustration of these points, we will now show, using the MLA scheme (which is a version of the LA scheme that we have adapted for FDDI-M), how the highest possible WCAU can be achieved under certain conditions.

Theorem 3

Any set of synchronous message streams with all P_i being multiple of the P_{min} and with its synchronous traffic loading rate not larger than $1-\alpha$ ($\alpha = \frac{t}{TTRT}$) can be guaranteed when the MLA scheme is used under the FDDI-M protocol.

***Proof*:**

Assume M is any set of synchronous message stream with all the P_i's are multiples of $TTRT$ and $U(M) \leq 1-\alpha$, then for all i, we have:

$$\sum_{i=1}^{n} H_i = \sum_{i=1}^{n} \frac{C_i}{\left\lfloor \frac{P_i}{TTRT} \right\rfloor} = \sum_{i=1}^{n} \frac{C_i}{\frac{P_i}{TTRT}} = TTRT \cdot \sum_{i=1}^{n} \frac{C_i}{P_i}$$

Note that if $\sum_{i=1}^{n} \frac{C_i}{P_i} = U(M) \leq 1-\alpha$, where $\alpha = \frac{t}{TTRT}$, then $\sum_{i=1}^{n} H_i \leq TTRT - \tau$, i.e. the protocol constraint can be satisfied. Since the deadline constraint is always satisfied when using the C_i-partitioning scheme, the set M can be guaranteed.

So, for those messages stream set in which all stream periods are multiples of the minimum period, the MLA scheme under FDDI-M protocol has the highest possible WCAU, that is $1-\alpha$. If there are enough synchronous traffic, the asynchronous traffic will be completely blocked. Note this scheme is not applicable to FDDI since it cannot meet the deadline constraint under FDDI.

5. Performance Evaluation of FDDI-M using Simulation

In this section, we will examine the actual performance of FDDI-M under heavily loaded network conditions, using a mixture of MPEG video traffic and some background asynchronous traffic to achieve the desirable loading conditions.

5.1 Model and Network Scenario

The simulation model used is very similar to that in (Shin and Zheng, 1995) to facilitate comparison. The network being simulated is a single FDDI ring with a ring length of 92 km and 50 attached stations. The station latency is 0.6 μsec and the propagation delay is 5.085 μsec/km, resulting in a ring latency (T_{ring}) of 0.5 msec. The maximum packet size follows the FDDI standard of 36 Kbits. Thus, the maximum packet transmission time (T_p) is 0.36 msec. Actual simulation is performed using the OPNET™ graphics simulation package. The OPNET package obtains a fairly detailed FDDI model, which we modified and adopted for our experiments.

The synchronous traffic is represented by MPEG video streams. Three classes of video streams are used. The main difference is the frame generation rate. Class I video streams generate 10 frames per sec. This class of traffic corresponds to applications with a lower quality requirement such as cartoon, animation and video conferencing. Class II video streams generate 30 frames per sec. This class corresponds to common video applications such as TV programs. Class III video streams generate 50 frames per sec. This class represents applications with high quality requirement such as HDTV. Stations belonging to the same class is grouped together in the ring such that under overload conditions the last station downstream in the class will suffer the most. Each frame is associated with a deadline which is the arrival time of the next frame. Thus the deadlines for the three classes of video streams are 100, 33 and 20 ms respectively. In a MPEG video streams, a large frame called a prime frame (P-frame) is generated for every eight frames. The size of a P-frame ranges from 100 Kbits to 150 Kbits and is assumed to be uniformly distributed. The frame size for the other frames ranges from 25 Kbits to 75 Kbits, again uniformly distributed.

Ten out of the 50 stations generate asynchronous traffic (standard Poisson arrivals). The asynchronous message size ranges from 0 to 1.5 Mbits, uniformly distributed. The total offered loading from the asynchronous traffic is 100 Mbps such that unused or excessive bandwidth left by the synchronous traffic will be utilized by the bandwidth-hungry asynchronous messages.

In our simulations FDDI and FDDI-M are compared in the context of five different SBA schemes. The SBA schemes chosen include both local and global, as well as both C_i-partitioning and *TTRT*-partitioning schemes. For FDDI, the *TTRT* value is set to one half of the minimum frame generation period of Class III traffic i.e. 20 / 2 msec = 10 msec. In our simulation, the protocol constraint is ignored in order to investigate the performance of the SBA schemes under overload conditions. For FDDI-M, the *TTRT* value is set to 20 - ΣH_i msec. The lower bound of the *TTRT* value is set to 2 msec in order to guarantee a certain level of asynchronous throughput.

We use station 0 to station (n-1) to generate the synchronous traffic streams. Asynchronous traffic is generated by station 40 to station 49. The simulation time is 100 sec. To simulate the worst case, all synchronous traffic streams start simultaneously. We only count the miss rate of P-frames since P-frames are more critical to the re-construction of the frame sequence; they are also much larger in size so they are much more likely to miss the their deadlines.

5.2 Results and Discussion

The miss rate of the P-frames for the FLA, ILA, PA, EPA and NPA Synchronous Allocation Schemes under both FDDI and FDDI-M are shown in Figures 1-5 respectively. These schemes encompass the various classes of SBA schemes given in Table 1.[2] The number of video streams is a multiple of 3 so that an equal number of video streams can come from each class. For instance, when the number of video streams is 30, stations 0 to 9 belong to class I, stations 10 to 19 belong class II and stations 20 to 29 belong to class III. The results are from the last downstream station in Class III. Having the most stringent timing requirement and being the last station downstream, this station should be the one most sensitive to the effect of the SBA schemes and medium access protocols used. Note that the focus of our simulation is on overload conditions. Theoretically, no more than $(TTRT - T_{ring} - T_p)/ H_i$ video streams should be established to ensure $\Sigma H_i \leq TTRT - T_{ring} - T_p$. Taking FLA as an example, a maximum of only 6 stations is allowed. Now, we experiment with 12 to 39 video streams which is far more than this maximum. We adopt this approach in our simulation experiments (which is similar to that used in the original paper on FDDI-M [1]), not only because overload condition is typically is of greater interest in practice, but also to facilitate comparison with the results obtained in that paper.

In general, we can see that the FDDI-M protocol performs better than the FDDI protocol, regardless of which SBA scheme is used. This is expected because the FDDI-M protocol allows the *TTRT* value to be the minimum period instead of one half the minimum period in the FDDI protocol, which effectively means that the FDDI-M network can support about twice as many synchronous streams as in FDDI. In the graphs, this is shown by the number of channels that can be supported without incurring a significant frame miss rate. An interesting observation is that the difference between the SBA schemes is not very large. The EPA scheme performs rather poorly, but Figures 1-5 show that the performance of the other schemes is quite similar. It is worth noting that the two schemes (FLA and ILA) which provide the best performance are both local schemes that are quite simple in their design. This suggests that implementing elaborate global schemes might not be worthwhile after all.

In fact, we observe that the local allocation schemes (Figures 1-3) outperform global ones (Figures 4-5)

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[2] The global C_i-partitioning schemes are not covered. The reason is that the MCA and EMCA schemes are quite restrictive and it is not possible to use them to overload the network as in the other schemes [20].

under the overload conditions simulated in our experiments. The reason is that the sum of the assigned bandwidth never exceeds the value of *TTRT* for global allocation schemes. While this may result in a more optimal allocation of the synchronous bandwidth under normal conditions, it also means that all stations attempt to partition the bandwidth which may be only sufficient for sending a single packet under overload conditions. As a result, a station may need to send the whole frame in a number of token visits. Even though the first one or two packets may arrive at the destination station in time, there is a greater chance that some of the packets will arrive late when the network is heavily loaded, which means the frame as a whole misses its deadline. On the other hand, in local allocation schemes the allocation of bandwidth to a station is independent of other stations and is typically non-optimal. Usually bandwidth is over-allocated when compared to the global schemes, but this may actually be an advantage in overload conditions since the MPEG frame can be transmitted using fewer token visits resulting in a higher chance for the frame to meet its deadline. As a result, performance degradation in global allocation schemes is more marked than in the local schemes when load increases.

While the curves shown in Figures 1-5 are typical of those given in performance evaluation of FDDI and FDDI-M, they show only the performance of the last station on the ring i.e. the worst case scenario. This is of course of paramount importance in the study of real-time traffic. However, it is interesting to study the behaviour of the other stations as well, an issue that is rarely covered in the literature. To better understand the dynamics of bandwidth allocation under overload conditions, we show the performance of the video streams at every station using the ILA scheme and FDDI. The three curves represent 3 different levels of loading, ranging from 27 to 39 total stations in the configuration (multiples of three used because there are three classes of video streams). It can be observed that the performance of the three classes of video streams is very different, and somewhat unexpected. All class I video streams enjoy low miss rate whereas all class II video streams suffer from a relatively high miss rate. For class III video streams, the performance of the stations degrades sharply in the downstream direction. For example, when there are 33 video streams, no frames from stations 0 to 10, which are class I video streams, miss their deadlines. However, the miss rates of stations 11 to 21, which generates class II video streams, are somewhat higher, ranging from 8% to 17%. For stations 22 to 32, which generates class III video streams, the miss rates rise rapidly from 6% to 50%.

This strange distribution of miss rates can be explained by the different amount of bandwidth assigned to stations in different classes. Figure 7 gives the bandwidth allocation to all stations using different SBA schemes in FDDI where there are 39 video streams. In the same figure, the transmission times required to transmit 1 to 4 packets are shown as well. Noted that a P-frame needs to be segmented into 3 to 5 packets for transmission. If the assigned bandwidth is not more than 2-packets transmission time, more than 1 token visit is required for the transmission of one whole P-frame. We will use ILA as a sample case. As can be seen in Figure 7, the H_i assigned to class I video streams for ILA is less than one packet transmission time. The H_i assigned to class II video streams is between two to three packet transmission time whereas, and that of class III, more than 4 packet transmission time. In the other words, class I video streams need 3 to 5 token visits in order to transmit one whole P-frame. Class II video streams need 2 token visits whereas class III video streams need only 1 token visit. Combined with the mean queuing delay for each packet given in Figure 8, it is not difficult to understand the poor performance of class II video streams and the large performance difference within class III video streams. Class I video streams do not have much problem meeting the deadline. Even though it may need 3 to 5 token visits to completely transmit a frame, its deadline is much longer (100 ms) and hence the low miss rate. Class III video streams all have a much tighter deadline (20 ms), but its allocated bandwidth is larger and a single token visit may be sufficient to transmit the entire frame. On the other hand, class II video streams require multiple number of token visits and a moderate deadline. Unfortunately, in a heavily loaded network, the token may not be able to go back to a particular station within one *TTRT*. As a result, the multiple number of token visits required for the transmission of a single frame may cause the frame to miss its deadline.

6. Conclusion

In this paper we have examined in depth the performance of the FDDI-M scheme in supporting synchronous traffic. We first classify the existing SBA schemes into two categories and pointed out certain properties regarding each of these two classes of SBA schemes. Next we examine the timing properties of FDDI-M by examining and examining their WCAU analytically, particularly for C_i-partitioning schemes where it is shown that FDDI-M is *not* always superior to FDDI. Next we use simulation to study how these SBA schemes fare under both FDDI and FDDI-M for MPEG video traffic transmission under heavily loaded conditions. The results are quite different from those based on WCAU, since we are examining overload conditions here and the miss rate is the performance metric. It is found that FDDI-M does offer significant improvement over FDDI for all SBA schemes, and that local SBA schemes outperform global schemes in the overload scenarios studied in our simulation studies. Thus we can conclude that even though FDDI-M does not always outperform FDDI in terms of WCAU, nevertheless when the network is heavily loaded it does manage to utilize the synchronous bandwidth more effectively and results in less synchronous messages missing their deadlines.

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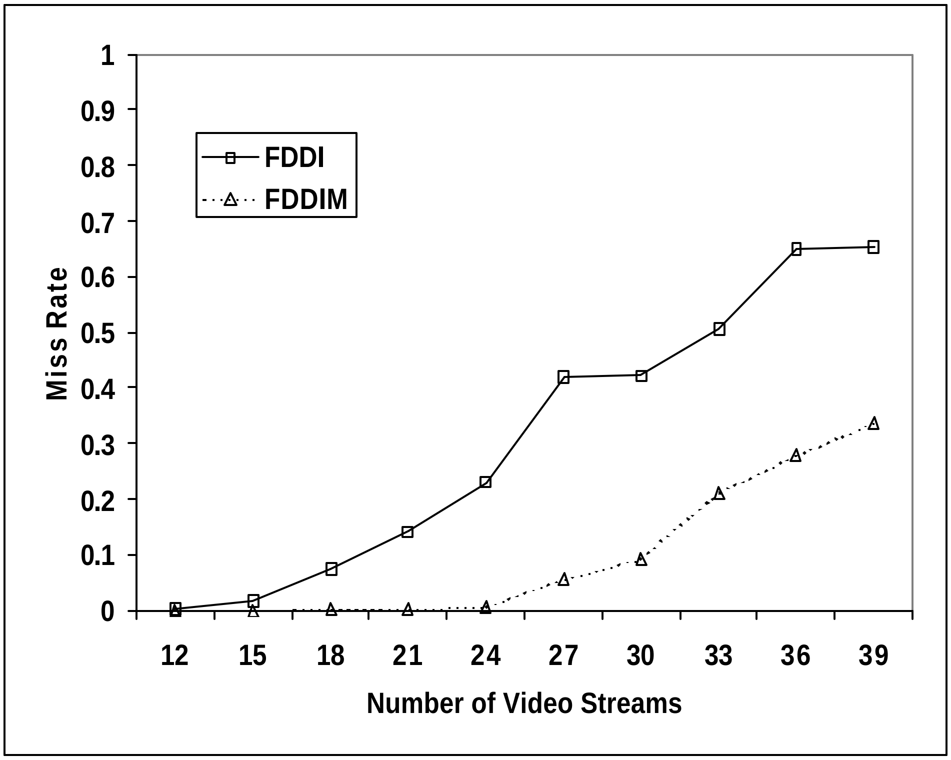

Figure 1: Full Length Allocation

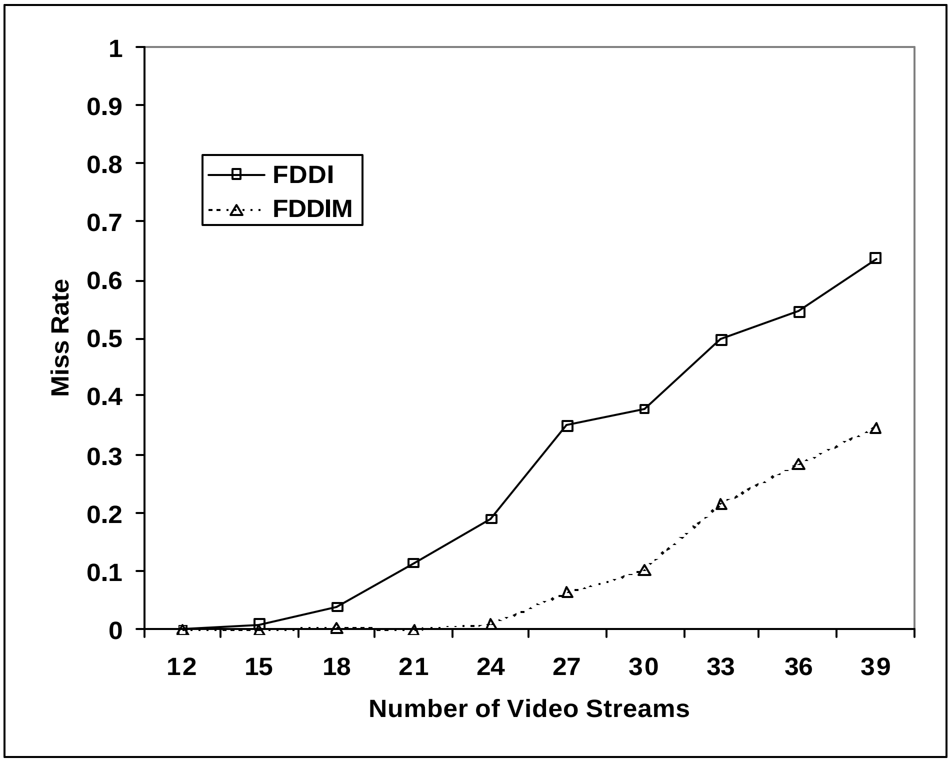

Figure 2: Improved Local Allocation

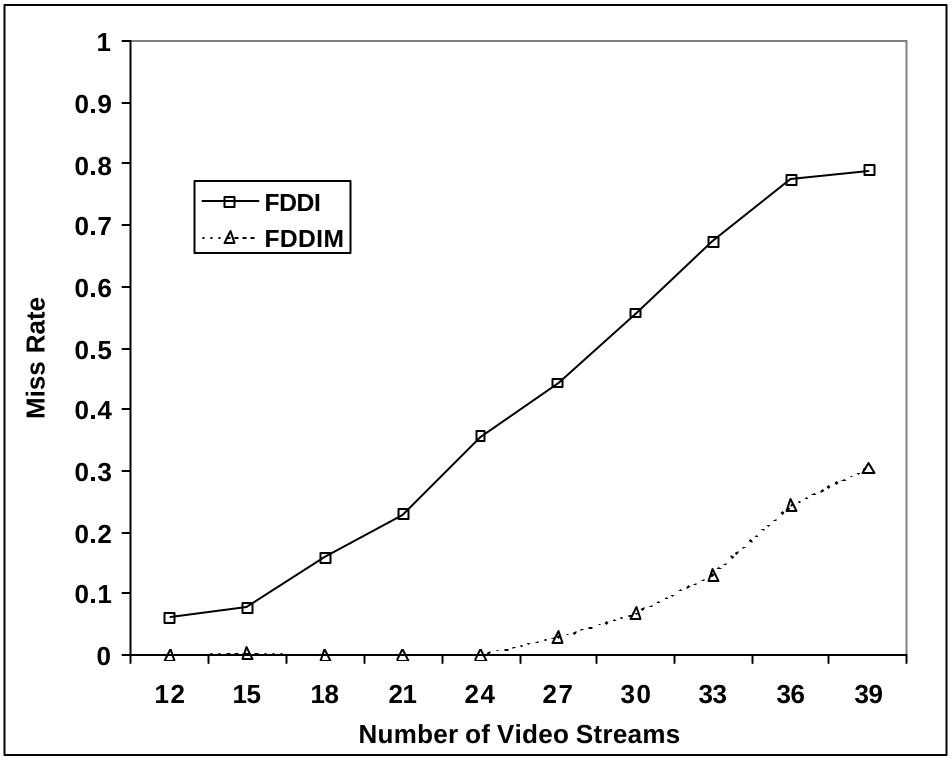

Figure 3: Proportional Allocation

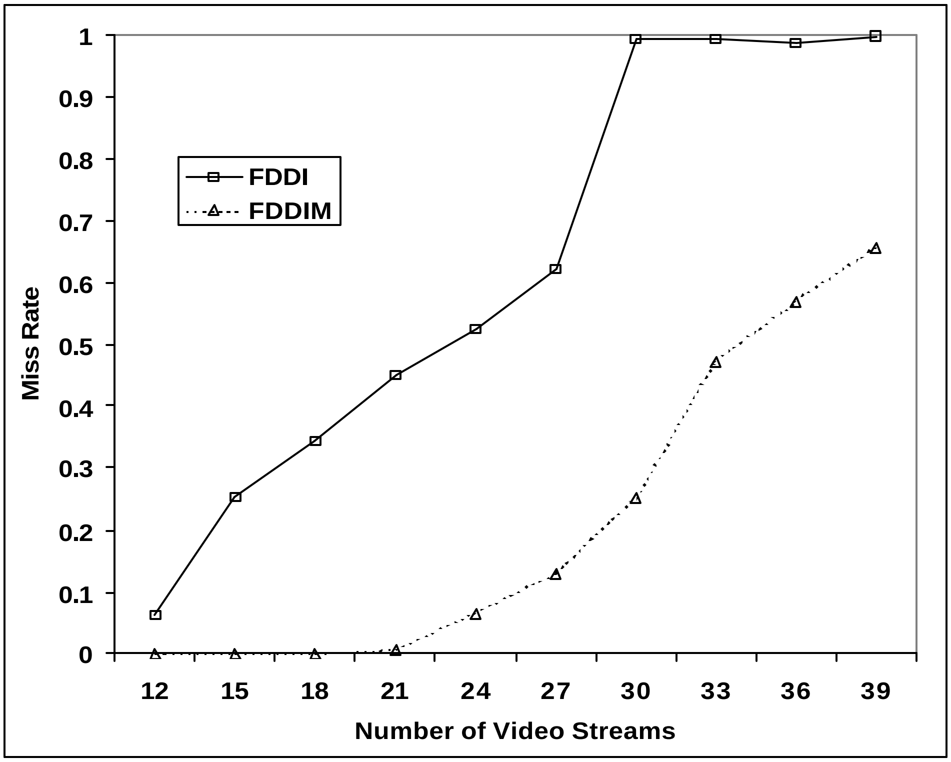

Figure 4: Equal Partition Allocation

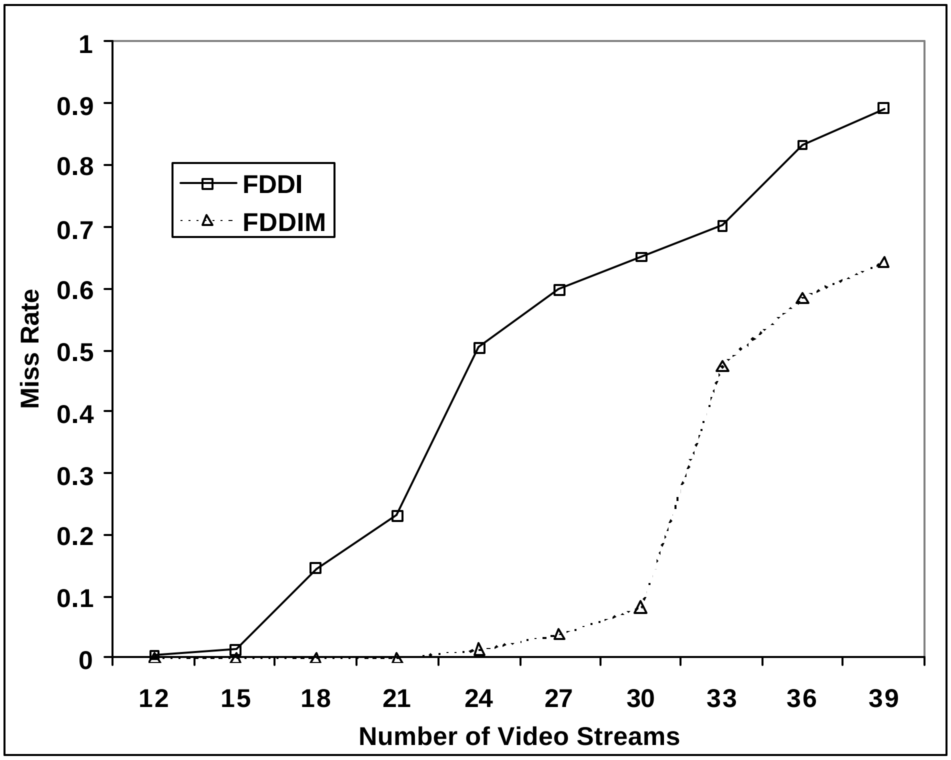

Figure 5: Normalized Proportional Allocation

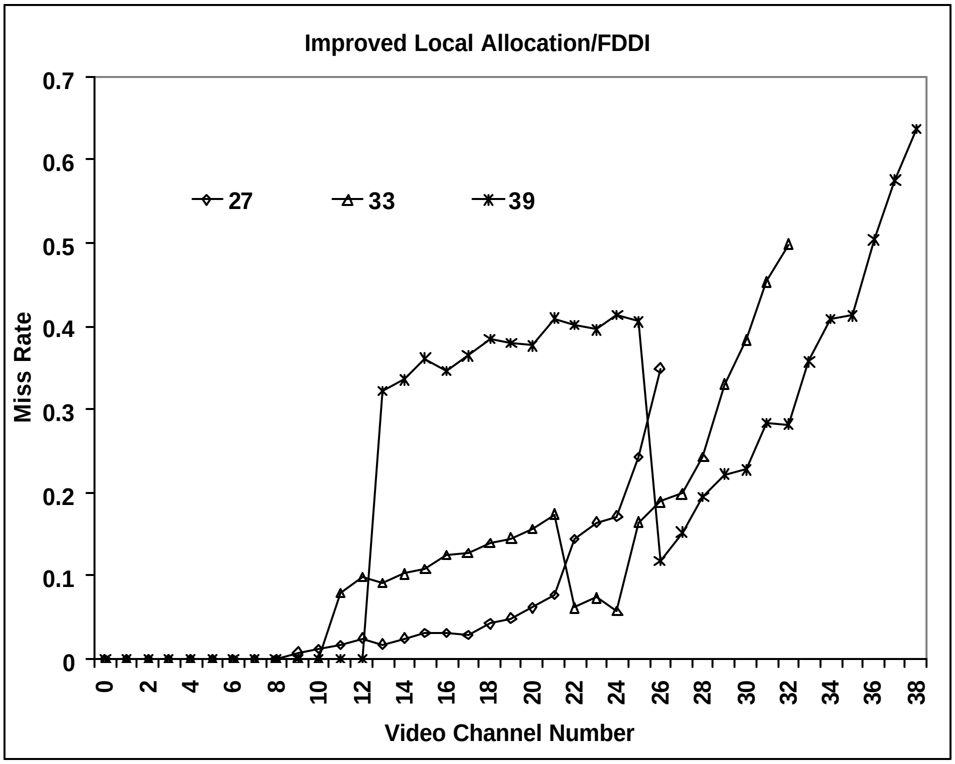

Figure 6: Improved Local Allocation

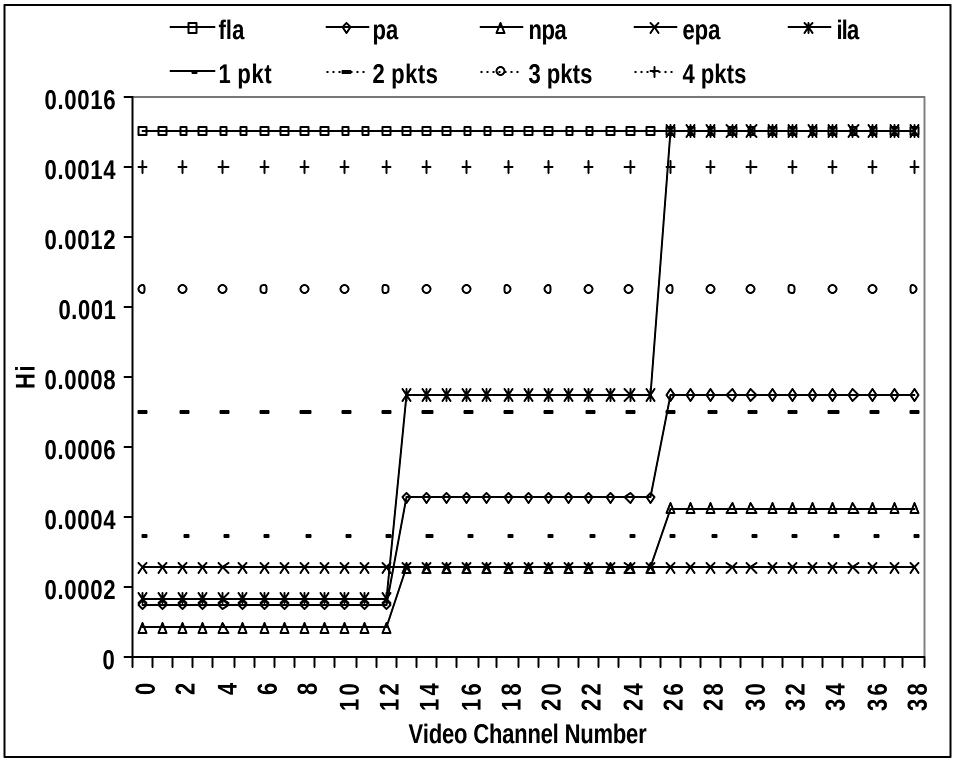

Figure 7: H_i Allocation

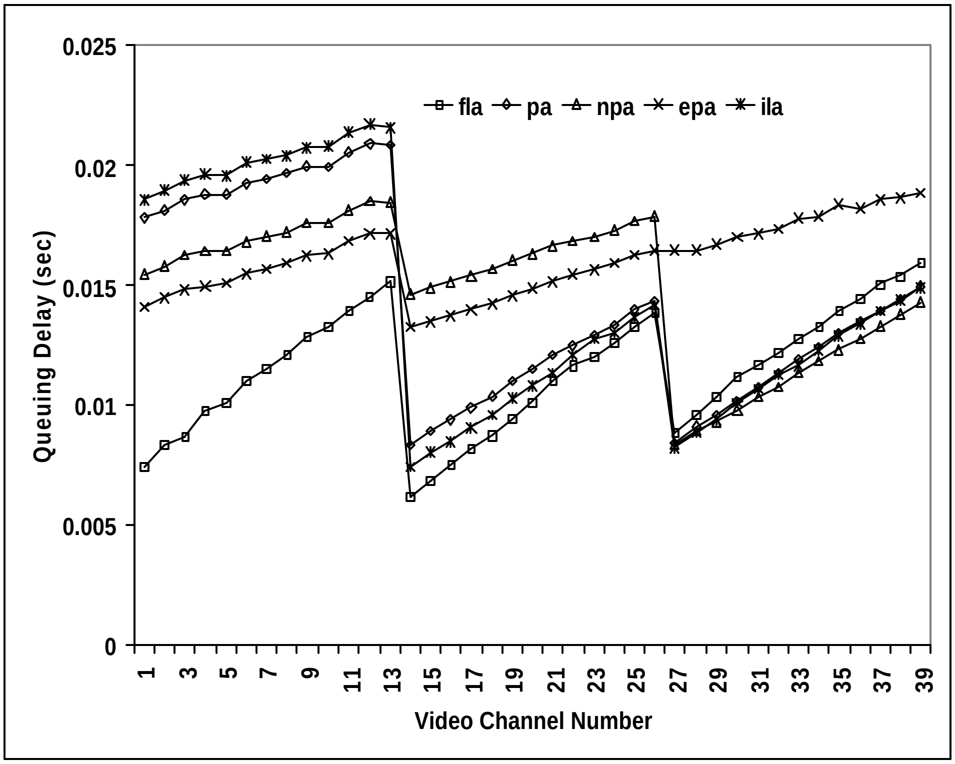

Figure 8: Queuing Delay