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# PERFORMANCE COMPARISONS OF ABT/IT AND DT IN ATM NETWORKS

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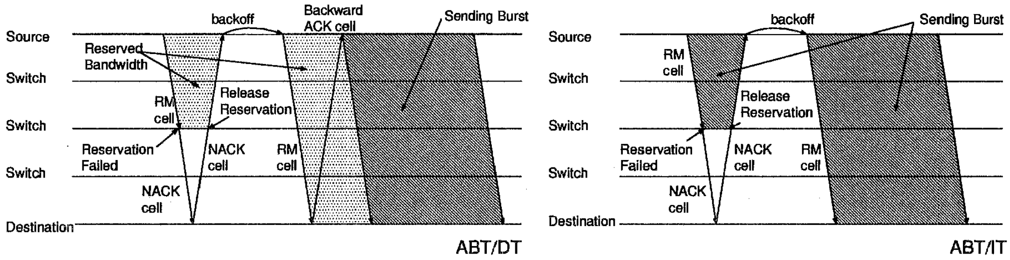
*Abstract* ATM Block Transfer (ABT) is promising for effectively transferring highly bursty data traffic in ATM networks. We develop an approximate analysis for two types of ABT (ABT/DT and ABT/IT) to discuss performance comparisons of ABT/IT and DT. Through numerical examples, we show that ABT/DT is quite sensitive to propagation delays while ABT/IT is not. We next investigate the performance improvement by dynamic bandwidth negotiation, which is applicable to ABT/DT. Bandwidth reduction methods in both of ABT/DT and IT are also examined. Simulation results show that the bandwidth negotiation can improve the performance of ABT/DT, and that in the case of short propagation delays, it outperforms even ABT/IT in terms of throughput. However, it is obtained at the expense of the increased burst transmission times. On the other hand, the bandwidth reduction allows a flexible use of the bandwidth, leading fairly good performance in all parameter regions.

## 1. Introduction

ATM (Asynchronous Transfer Mode) has been developed as a new network technology to integrate various media through a unified interface. In two standardization bodies, ITU-T and ATM Forum, several service classes have been defined according to the required QoS (Quality of Service) of the multimedia traffic [1] [2] [3]. Those are CBR (Constant Bit Rate), VBR (Variable Bit Rate), ABR (Available Bit Rate) and UBR (Unspecified Bit Rate) service classes. In CBR and VBR service classes, a fixed amount of resources is actually or virtually allocated to each connection to support real–time communications such as motion video and audio transmission [3]. To guarantee QoS in those service classes, however, the source must know traffic characteristics in advance of the connection establishment. Further, those two classes cannot efficiently utilize the bandwidth when too highly bursty traffic is applied because the connection cannot emit cells exceeding the negotiated bandwidth. Those are reasons that the ABR service class has been standardized in the ATM Forum for data communications [4]. In the ABR service class, a reactive congestion control mechanism is defined for existing bursty data communications, and its main concern is to guarantee a cell loss ratio. However, careful parameter tuning is necessary to guarantee no cell loss, and a set of optimal control parameters can be chosen only when the number of active connections are fixed or at least it should accurately be estimated [4]. The UBR service class does not guarantee any QoS parameter.

Another service class, ABT (ATM Block Transfer) [1] [5] [6] service class, is also intended to be applied to data communications. A difference from the ABR service class is that the bandwidth is explicitly reserved before cell emission. In that sense, the ABT service class is similar to CBR/VBR service classes. However, bandwidth reservation is not performed at the connection setup time, but is deferred to time when the burst actually arrives at the source. Here, the burst means the data unit of ABT. For example, the burst may correspond



(a) ABT/DT (b) ABT/IT

Figure 1: ABT Protocols

to the file or block in the case of file transfer. Once the bandwidth reservation is admitted by the network, the source can transmit the burst with no cell loss. It can allow the high utilization of network resources without knowledge of traffic characteristics, and be expected to be suitable to bursty data transfer.

More specifically, ABT protocol is performed as follows. When the burst arrives at the source, a forward RM (Resource Management) cell is sent to the destination on the route, which has been established during the connection setup phase. The RM cell contains the required bandwidth to transfer the burst, and each switch on the route reserves the bandwidth according to the RM cell, and forwards the RM(ACK) cell to the next switch in the downstream. If a sufficient amount of the bandwidth is not available on the link, on the other hand, the switch forwards the RM(NACK) cell to the destination. The destination then returns the RM(ACK) or RM(NACK) cell to the source as the backward RM cell. Every switch receiving the backward RM(NACK) cell releases the reserved bandwidth. The source receiving the backward RM cell can finally recognize whether the bandwidth request is admitted or not. This is called ABT with Delayed Transmission (ABT/DT), and is illustrated in Fig. 1(a).

When the bandwidth becomes large as in recent high speed networks, the overhead time to wait the backward RM cell before the burst transmission is not acceptable. That is the reason why ABT/IT (ABT with Immediate Transmission) is introduced [5]. In ABT/IT, the source sends the burst immediately following the forward RM cell without acknowledge of the reservation as shown in Fig. 1(b). If the sufficient bandwidth is available, each switch accepts the burst to forward it to the next switch in the downstream. If not, on the other hand, the switch rejects the incoming burst, and returns the backward RM(NACK) cell via the destination to notify the source that the burst is lost. While this mechanism introduces a hardware complexity to selectively discard the burst, it must alleviate the influence of the large propagation delay. Our main subject of this paper is then to quantitatively investigate how the performance can be improved by ABT/IT when comparing with ABT/DT. For this purpose, we will newly develop an approximate analytic methods of ABT/DT and IT in Section 2. The comparative results are next presented in Section 3.

In the above, we have assumed that each switch reserves the bandwidth equal to the one specified in the forward RM cell. In the case of ABT/DT, however, it is possible that the switch reserves the bandwidth less than the requested bandwidth specified in the RM cell if the latter is not available on the link. The switch then overwrites the new bandwidth on the RM cell to forward it to the next switch. In this bandwidth reservation method, each switch checks the bandwidth in the backward RM cell, and reduces the reserved bandwidth if the temporarily reserved bandwidth is larger than the one in the backward RM cell. The source receiving the backward RM(ACK) cell then starts to transmit the burst according to the bandwidth specified in the RM cell. Note that such a mechanism is impossible in ABT/IT since the source emits the burst immediately after the RM cell. We will examine the effect of such a dynamic bandwidth reservation mechanism through simulation in Subsection 4.1.

Another way to allow flexible bandwidth reservation may be implemented in the backoff algorithm. When the source fails to reserve the bandwidth, it may again try bandwidth reservation after some time interval, which is called "backoff". Since rejection of the bandwidth reservation indicates that some switch falls into congestion, it is more likely that the reservation request can be accepted with reduced bandwidth. Both of ABT/DT and IT protocols can allow such a backoff mechanism, and its effect will be investigated by simulation in Subsection 4.2.

As related works, the authors in [7] have compared ABT/IT and DT with an arbitrary network topology, and observed that ABT/DT is sensitive to propagation delays. However, the model in [7] assumed that the switch holds its reserved bandwidth even after the backward RM(NACK) cell has received in ABT/IT. Such an unrealistic assumption lead a limited performance of ABT/IT. Further, the requested bandwidth is assumed to be fixed while a more flexible bandwidth usage can allow performance improvement as we will demonstrate in Section 4.

Another study to treat the bursty traffic can be found in [8] [9] where the authors introduced an architecture for a class of packet switching networks, called *burst scheduling networks*. Its objective is to guarantee the end-to-end delay and delay jitter for efficiently transferring the bursty data. More recently, they notice that their architecture is similar to ABT, and in [10], they describe their architecture in the context of ABT protocols. In their paper, however, they focus on the implementation issue of the admission control algorithm based on ABT to guarantee the burst transfer delay and loss rate, and they have not referred to a possibility of failures of the reservation requests. On the other hand, we develop an approximate analysis of blocking probability of bursts in ABT/IT and DT.

Other studies on ABT can be found in [11] [12] [13], but those are limited to ABT/DT. In [11] [12], the authors have shown the effect of introducing the dynamic bandwidth negotiation to ABT/DT using the single link model. They extend the model to a network with an arbitrary topology to verify that the observations in [11] [12] can also be applied to general networks in [13]. However, they assumed the propagation delay is negligible [13]. On the contrary, in this paper, we first investigate the basic performance of ABT/IT and DT for the arbitrary network with non–zero propagation delay by developing the approximate analysis. We then show the effect of flexible bandwidth usage through simulation experiments by virtue of the bandwidth negotiation method in ABT/DT and backoff methods in both of ABT/DT and IT.

This paper is organized as follows. In Section 2, we introduce the approximate analysis of ABT/DT and IT. Using our analytic approach, we present performance comparisons between ABT/DT and IT in Section 3. We discuss the performance improvement by the bandwidth negotiation method of ABT/DT in Subsection 4.1 and by backoff algorithms in Subsection 4.2, respectively. Finally, we conclude our paper in Section 5.

## 2. Analysis of ABT

### 2.1. Mathematical Model and Assumptions

Consider a network with $J$ ($> 0$) links, labeled 1 to $J$. Link $j$ ($j = 1, \ldots, J$) has capacity $B_j$ (Mbps). Adjacent two links are connected by a node (i.e., an ATM switch). Every terminal is connected to the end node. We assume that every end node pair has a predefined route (i.e., fixed routing strategy), and that the ATM SVC (Switched Virtual Connection) has already been established along the route between every two terminals. Each end node has a number of terminals such that the arrivals of bursts can be assumed to follow a Poisson distribution. Then, we regard multiple SVCs on the route between two end node pair as an aggregated single *connection*. The number of asymmetric one-way *connections* in the network is denoted by $P$, and the bandwidth is not reserved for each connection until the burst is actually generated at the source of the connection according to the ABT protocol.

To analyze the performance of the above network, we assume the followings. All links is assumed to have the same length and we denote the round-trip propagation delay of a link by $D$. Let $J^{(p)}$ ($p = 1, \ldots, P$) denote a set of links on the route of connection $p$. For $j \in J^{(p)}$, let $J^{(p)}_{j+}$ (resp. $J^{(p)}_{j-}$) denote a set of links between the source (resp. the destination) and link $j$ on the route. Thus, $J^{(p)} = J^{(p)}_{j+} \cup j \cup J^{(p)}_{j-}$ for $j \in J^{(p)}$. Let $H$ denote the maximum number of links among all routes, i.e., $H = \max_p |J^{(p)}|$. Bursts on the $p$th connection are generated according to a Poisson process with rate $\lambda_p$. Lengths of bursts of all connections are independent and identically distributed according to an exponential distribution with mean $1/\mu$ (Mbit). By assuming that all bursts are transmitted with $B$ Mbps, transmission times of all bursts are exponentially distributed with mean $(\mu b)^{-1}$ (sec). Let $R^{(h)}_j$ ($j = 1, \ldots, J, h = 1, \ldots, H$) denote a set of connections which has link $j$ as the $h$th link from their destinations. Further, let $R_j$ ($j = 1, \ldots, J$) denote a set of connections having link $j$ on their routes, i.e., $R_j = \cup_{h=1}^{H} R^{(h)}_j$. We then assume $\sum_{p \in R_j} \lambda_p/\mu < B_j$ for all $j = 1, \ldots, J$, which ensures that the network resources are ample for supporting all connections. We assume that the overhead of RM cell transmissions are negligible. We also assume that the network is stable and has reached its steady state in the rest of the paper.

### 2.2. Analytical Approach

The mathematical model is considered as a variant of loss networks. However, since we explicitly model propagation delays, the network does not have the product-form solution. Thus we do not expect any solution methods to evaluate the throughput performance exactly. We therefore provide an approximate analysis to obtain the throughput performance. We first adopt the reduced load approximation which is a common technique to analyze large-scale loss networks. The essential point in the reduced load approximation is to treat all links independently, while the influence of other links on the target link is taken into account by reducing the load on the target link. As for the reduced load approximation, readers are referred to [14] [15] [16] [17] [18] [19].

By virtue of the reduced load approximation, the throughput $\theta_p$ (Mbps) of connection $p$ is given by

$$\theta_p = \frac{\lambda_p}{\mu} \prod_{j \in J^{(p)}} (1 - E_j), \tag{2.1}$$

where $E_j$ denotes the blocking probability on link $j$. In what follows, we analyze the blocking probabilities in ABT/IT and ABT/DT separately.

## 2.3. Blocking Probabilities in ABT/IT

Let $\boldsymbol{n}_j$ denote the state of link $j$:

$$\boldsymbol{n}_j = (n_{j,1}, n_{j,2}, \ldots, n_{j,H}),$$

where $n_{j,1}$ denotes the number of bursts being successfully transmitted on link $j$ and $n_{j,h}$ $(h = 2, \ldots, H)$ denotes the number of bursts in transmission on link $j$, whose connection is in $R_j^{(h)}$, while being failed in transmission in one of the downstream links on the route. We define $h(\boldsymbol{n}_j)$ as the remaining amount of bandwidth given $\boldsymbol{n}_j$:

$$h(\boldsymbol{n}_j) = B_j - b\sum_{h=1}^{H} n_{j,h}.$$

Let $S_j$ be

$$S_j = \{\boldsymbol{n}_j \mid h(\boldsymbol{n}_j) \le B_j, n_{j,h} \ge 0 \ (h = 1, \ldots, H)\}, \qquad j = 1, \ldots, J.$$

Note that $S_j$ denotes a feasible set of states of link $j$.

We now consider holding times of bursts from connection $p \in R_j^{(h)}$ $(h = 2, \ldots, H)$ on link $j$, which fail in transmission in one of downstream links on the route. Note that the failure of the transmission is notified after time $hD$. Thus, if the transmission time of a failed burst is longer than $hD$, the holding time is given by $hD$. Otherwise, the holding time is identical to the transmission time. Therefore the distribution of holding times of failed bursts is given by a truncated exponential distribution with a mass at $hD$, whose mean $\mu_h^{-1}$ is given by

$$\mu_h^{-1} = \frac{1 - e^{-\mu b h D}}{\mu b}.$$

We define a $1 \times H$ unit vector $\boldsymbol{e}_h$ $(h = 1, \ldots, H)$ as

$$\boldsymbol{e}_h = (0, \ldots, 0, \underset{h\text{th}}{1}, 0, \ldots, 0).$$

The transition from state $\boldsymbol{n}_j$ to state $\boldsymbol{n}_j + \boldsymbol{e}_1$ happens with rate $r_{j,1}$, where

$$r_{j,1} = \begin{cases} \sum_{p \in R_j} \lambda_p \prod_{k \in J_{j+}^{(p)}} (1 - E_k) \prod_{k \in J_{j-}^{(p)}} (1 - E_k), & \text{if } \boldsymbol{n}_j \in S_j, h(\boldsymbol{n}_j) > b, \\ 0, & \text{otherwise.} \end{cases} \tag{2.2}$$

Note that empty products are defined to be one in the above and hereafter. Further the transition from state $\boldsymbol{n}_j$ to state $\boldsymbol{n}_j + \boldsymbol{e}_h$ $(h = 2, \ldots, H)$ happens with rate $r_{j,h}$, where, for $h = 2, \ldots, H$,

$$r_{j,h} = \begin{cases} \sum_{p \in R_j^{(h)}} \lambda_p \prod_{k \in J_{j+}^{(p)}} (1 - E_k) \left[ 1 - \prod_{k \in J_{j-}^{(p)}} (1 - E_k) \right], & \text{if } \boldsymbol{n}_j \in S_j, h(\boldsymbol{n}_j) > b, \\ 0, & \text{otherwise.} \end{cases} \tag{2.3}$$

Note here that all bursts are generated according to Poisson processes. Therefore we approximate the arrival process from each connection to link $j$ by a Poisson process and we aggregate all arrivals into one Poisson stream. The traffic intensity $\rho_j$ of the aggregated stream in link $j$ is given by

$$\rho_j = r_{j,1}(\mu b)^{-1} + \sum_{h=2}^{H} r_{j,h}\mu_h^{-1}.$$

Let $N_j$ be

$$N_j = n_{j,1} + \ldots + n_{j,h}$$

It then follows from the insensitivity property of $M/G/c/c$ that [20]

$$\Pr(N_j = k) = \frac{\rho_j^k/k!}{\sum_{i=0}^{K_j} \rho_j^i/i!}, \qquad k = 0, 1, \ldots, K_j,$$

where $K_j$ denotes the maximum integer which is not greater than $B_j/b$. Thus the blocking probability $E_j$ on link $j$ is given by

$$E_j = \Pr(N_j = K_j) = \frac{\rho_j^{K_j}/K_j!}{\sum_{i=0}^{K_j} \rho_j^i/i!}, \tag{2.4}$$

We now provide an iterative procedure to obtain the blocking probability $E_j$. In what follows, for any symbol $X$, we denote the value of $X$ in the $n$th iteration by ${}_{(n)}X$ .

Step 1. Initial input: for all $p = 1, \ldots, P$ and all $j = 1, \ldots, J$,

i) Let ${}_{(0)}E_j = 0$

ii) Let ${}_{(0)}\theta_p = \lambda_p/\mu$.

iii) Set a nonnegative small value to $\epsilon$ (e.g., $\epsilon = 10^{-3}$ for graphical representations).

iv) Let $n = 1$.

Step 2. The $n$th iteration:

i) Compute the arrival rates $r_{j,h}$ $(h = 1. \ldots, H)$ in (2.2) a nd (2.3) for all $j = 1, \ldots, J$ with ${}_{(n-1)}E_j$.

ii) Compute the right hand side of (2.4) and let ${}_{(n)}E_j$ be the resulting value.

Step 3. Convergence check

i) Compute ${}_{(n)}\theta_p$ in (2.1) for all $p = 1, \ldots, P$ with ${}_{(n)}E_j$.

ii) Let

$$Z = \sum_{p=1}^{P} |{}_{(n)}\theta_p - {}_{(n-1)}\theta_p| / {}_{(n)}\theta_p.$$

iii) If $Z \leq \epsilon$, we adopt ${}_{(n)}\theta_p$ $(p = 1, \ldots, P)$ as approximate solutions to $\theta_p$. Otherwise, add one to $n$ and go to Step 2.

Even though we could not prove the convergence of the above iterative procedure, it converged in all of our numerical experiments shown in Section 3.

## 2.4. Blocking Probabilities in ABT/DT

Let $\boldsymbol{m}_j$ denote the state of link $j$:

$$\boldsymbol{m}_j = (m_{j,1}^{(1)}, \dots, m_{j,H}^{(1)}, m_{j,2}^{(2)}, \dots, m_{j,H}^{(2)}),$$

where $m_{j,h}^{(1)}$ $(1 \le h \le H)$ denotes the number of bursts being successfully transmitted on link $j$ and having $h$ hops, and $m_{j,h}^{(2)}$ $(h = 2, \dots, H)$ denotes the number of bursts in transmission on link $j$, whose connection is in $R_j^{(h)}$, while being failed in transmission in one of the downstream links on the route. We define $h(\boldsymbol{m}_j)$ as the remaining amount of bandwidth given $\boldsymbol{m}_j$:

$$h(\boldsymbol{m}_j) = B_j - b\sum_{h=1}^{H} m_{j,h}^{(1)} - b\sum_{h=2}^{H} m_{j,h}^{(2)}.$$

Further we re-define $S_j$ as

$$S_j = \{\boldsymbol{m}_j \mid h(\boldsymbol{m}_j) \le B_j, m_{j,h}^{(1)} \ge 0\,(h = 1, \dots, H), m_{j,h}^{(2)} \ge 0\,(h = 2, \dots, H)\}, \qquad j = 1, \dots, J.$$

Note that $S_j$ denotes a feasible set of states of link $j$.

We now consider holding times of reservations from connection $p \in R_j^{(h)}$ $(h = 2, \dots, H)$ on link $j$, which fail in reservation in one of downstream links on the route. Note that the failure of the transmission is notified after time $hD$. Thus, the holding time is given by $hD$. On the other hand, when the connection $p$ succeeds in reservation, the mean holding time $\mu_p^{-1}$ of the connection $p$ in each link is given by

$$\mu_p^{-1} = (\mu b)^{-1} + h_p^* D,$$

where $h_p^* = |J^{(p)}|$ denotes the number of links on the route of connection $p$ (i.e., the number of hops of connection $p$).

We re-define a $1 \times (2H-1)$ unit vector $\boldsymbol{e}_h$ $(h = 1, \dots, 2H-1)$ as

$$\boldsymbol{e}_h = (0, \dots, 0, \underset{h\text{th}}{1}, 0, \dots, 0).$$

The transition from state $\boldsymbol{m}_j$ to state $\boldsymbol{m}_j + \boldsymbol{e}_h$ $(h = 1, \dots, H)$ happens with rate $r_{j,h}^{(s)}$, where, for $h = 1, \dots, H$,

$$r_{j,h}^{(s)} = \begin{cases} \sum_{p \in R_j^{(h)}} \lambda_p \prod_{k \in J_{j+}^{(p)}} (1 - E_k) \prod_{k \in J_{j-}^{(p)}} (1 - E_k), & \text{if } \boldsymbol{m}_j \in S_j, h(\boldsymbol{m}_j) > b, \\ 0, & \text{otherwise,} \end{cases} \tag{2.5}$$

where $H^{(h)}$ denotes the set of connections having $h$ hops on their routes. Further the transition from state $\boldsymbol{m}_j$ to state $\boldsymbol{m}_j + \boldsymbol{e}_{H-1+h}$ $(h = 2, \dots, H)$ happens with rate $r_{j,h}^{(f)}$, where, for $h = 2, \dots, H$,

$$r_{j,h}^{(f)} = \begin{cases} \sum_{p \in R_j^{(h)}} \lambda_p \prod_{k \in J_{j+}^{(p)}} (1 - E_k) \left[1 - \prod_{k \in J_{j-}^{(p)}} (1 - E_k)\right], & \text{if } \boldsymbol{m}_j \in S_j, h(\boldsymbol{m}_j) > b, \\ 0, & \text{otherwise.} \end{cases} \tag{2.6}$$

Note again that all bursts are generated according to Poisson processes. Therefore we approximate the arrival process from each connection to link $j$ by a Poisson process and we aggregate all arrivals into one Poisson stream. The traffic intensity $\rho_j$ of the aggregated stream in link $j$ is given by

$$\rho_j = \sum_{h=1}^{H} r_{j,h}^{(s)} \left\{ (\mu b)^{-1} + hD \right\} + \sum_{h=2}^{H} r_{j,h}^{(f)} hD.$$

Let $M_j$ be

$$M_j = \sum_{h=1}^{H} m_{j,h}^{(1)} + \sum_{h=2}^{H} m_{j,h}^{(2)}$$

It then follows from the insensitivity property of $M/G/c/c$ that [20]

$$\Pr(M_j = k) = \frac{\rho_j^k / k!}{\sum_{i=0}^{K_j} \rho_j^i / i!}, \qquad k = 0, 1, \ldots, K_j,$$

where $K_j$ denotes the maximum integer which is not greater than $B_j/b$. Thus the blocking probability $E_j$ on link $j$ is given by

$$E_j = \Pr(M_j = K_j) = \frac{\rho_j^{K_j} / K_j!}{\sum_{i=0}^{K_j} \rho_j^i / i!}, \tag{2.7}$$

We now provide an iterative procedure to obtain the blocking probability $E_j$. In what follows, for any symbol $X$, we denote the value of $X$ in the $n$th iteration by ${}_{(n)}X$ .

Step 1. Initial input: for all $p = 1, \ldots, P$ and all $j = 1, \ldots, J$,

i) Let ${}_{(0)}E_j = 0$

ii) Let ${}_{(0)}\theta_p = \lambda_p / \mu$.

iii) Set a nonnegative small value to $\epsilon$ (e.g., $\epsilon = 10^{-3}$ for graphical representations).

iv) Let $n = 1$.

Step 2. The $n$th iteration:

i) Compute the arrival rates $r_{j,h}^{(s)}$ $(h = 1. \ldots, H)$ in (2.5) and the arrival rates $r_{j,h}^{(f)}$ $(h = 2. \ldots, H)$ in (2.6) for all $j = 1, \ldots, J$ with ${}_{(n-1)}E_j$.

ii) Compute the right hand side of (2.7) and let ${}_{(n)}E_j$ be the resulting value.

Step 3. Convergence check

i) Compute ${}_{(n)}\theta_p$ in (2.1) for all $p = 1, \ldots, P$ with ${}_{(n)}E_j$.

ii) Let

$$Z = \sum_{p=1}^{P} |{}_{(n)}\theta_p - {}_{(n-1)}\theta_p| / {}_{(n)}\theta_p.$$

iii) If $Z \leq \epsilon$, we adopt ${}_{(n)}\theta_p$ $(p = 1, \ldots, P)$ as approximate solutions to $\theta_p$. Otherwise, add one to $n$ and go to Step 2.

Even though we could not prove the convergence of the above iterative procedure, it converged in all of our numerical experiments shown in Section 3.

## 3. Performance Comparisons of ABT/DT and IT

### 3.1. Network Model

In this section, we compare performances of ABT/DT and IT based on the approximate analysis presented in the previous section. We use the tandem network model with two links throughout this paper (see Fig. 2) except Subsection 3.5, where a more general network model is treated to show that observations made in Subsections 3.3 and 3.4 are also applicable to more general network topologies.

As shown in Fig. 2, two–hop connection C1 contends with one–hop connection C2 for link L1, and does with another one–hop connection C3 for link L2. The capacities of two ATM links, $B_j$ ($j$ = L1, L2), are identically set to 150 Mbps. The generation rate of bursts at sources are identically set to $\lambda_0$, i.e., $\lambda_p = \lambda_0$ ($p$ = C1, C2, C3). The mean burst length, $1/\mu$, is 5 Kbits, corresponding to 33 $\mu$sec on 150 Mbps link. The propagation delays of links L1 and L2 are varied from 1 $\mu$sec to 1 msec.

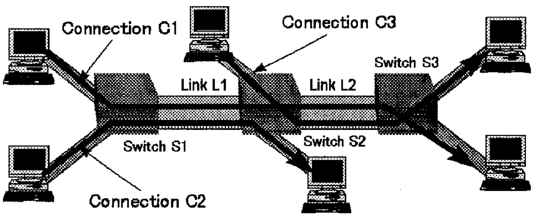


Figure 2: Network Model

### 3.2. Accuracy of Our Approximate Analysis

We first assess the accuracy of our approximate analysis by comparing with simulation. In Figs. 3 and 4, we compare blocking probability values of ABT/IT with 1 $\mu$sec and 1 msec propagation delays, respectively. The requested bandwidth $b$ is set to be 75 Mbps. Simulation results are shown with 95% confidence intervals. We can observe good agreements between analysis and simulation results. The corresponding results for ABT/DT are also plotted in Figs. 5 and 6. Excellent accuracies can also be observed in those figures.

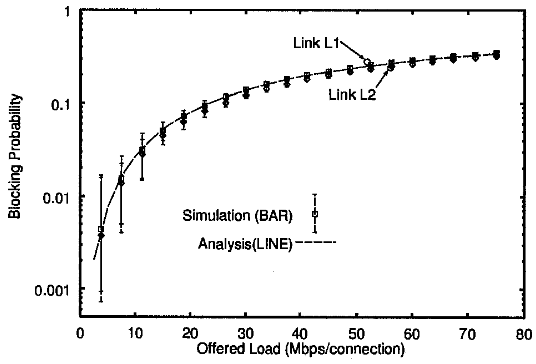


Figure 3: Comparisons of Analysis and Simulation (ABT/IT, Propagation Delay = 1 $\mu$sec)

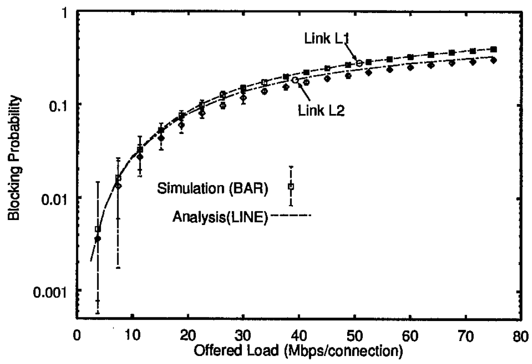


Figure 4: Comparisons of Analysis and Simulation (ABT/IT, Propagation Delay = 1 msec)

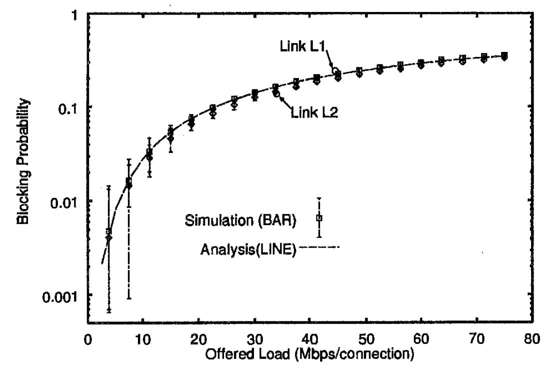


Figure 5: Comparisons of Analysis and Simulation (ABT/DT, Propagation Delay = 1 $\mu$sec)

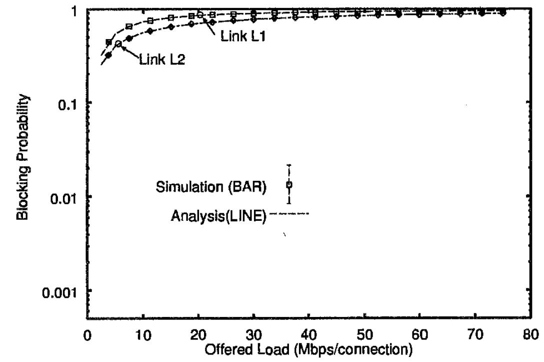


Figure 6: Comparisons of Analysis and Simulation (ABT/DT, Propagation Delay = 1 msec)

## 3.3. Effect of Offered Load on Throughput

Recalling that throughputs can directly be calculated from the blocking probability (see, eq. (1)), we first compare throughputs of ABT/DT and IT against the offered load ($\lambda_0/\mu$) in Fig. 7. The propagation delay of each link is set to be 1 $\mu$sec, and the requesting bandwidth $b$ is 50 Mbps. In the figure, results for three connections C1, C2 and C3 are displayed. Since connection C1 is two–hop connection, its throughput is degraded as the offered load becomes high. The difference between ABT/DT and IT cannot be observed in the case of the short propagation delay.

The difference becomes significant when the propagation delay is set to be 1 msec as shown in Fig. 8. In the case of ABT/DT, the large propagation delay leads to the larger blocking probability of link L1 and henceforth lower throughput of connection C1. The offered load on link L2 then becomes smaller than that of link L1. It is the reason that the throughput of connection C3 is less degraded than those of other connections.

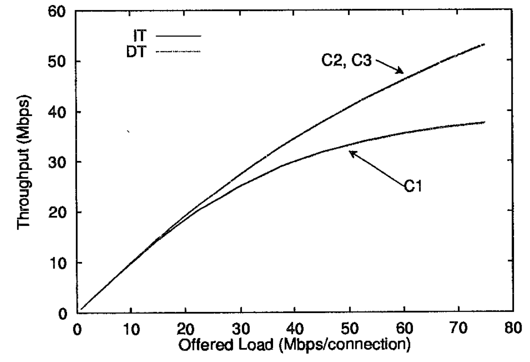


Figure 7: Throughput vs. Offered Load (Propagation Delay = 1 $\mu$sec)

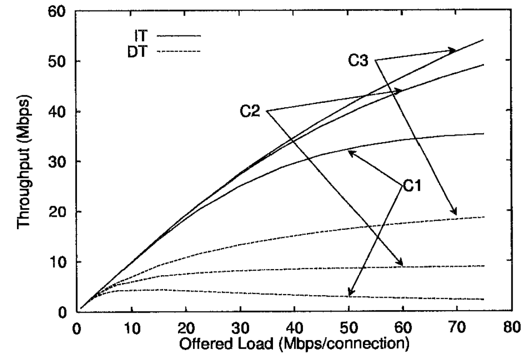


Figure 8: Throughput vs. Offered Load (Propagation Delay = 1 msec)

## 3.4. Effect of Propagation Delay on Throughput

The effect of the propagation delay is illustrated more clearly in Fig. 9, where the throughput of connection C1 against the propagation delay is shown. In obtaining the figure, the requesting bandwidth $b$ is set to be 50 Mbps, and the offered load on the link is varied as $\rho$ = 0.9 (135 Mbps), 0.5 (75 Mbps) and 0.1 (15 Mbps). We can observe the throughput of ABT/DT is degraded suddenly when the propagation delay becomes around 0.1 msec, and reaches almost zero when the propagation delay is 10 msec. Those values of propagation delays correspond to 20 Km and 2000 Km long, respectively. Namely, ABT/DT is not applicable to metropolitan and wide area networks. The throughput of ABT/IT is also degraded by the large propagation delay, but the influence is very small because the bandwidth reservation time is not affected by the propagation delays.

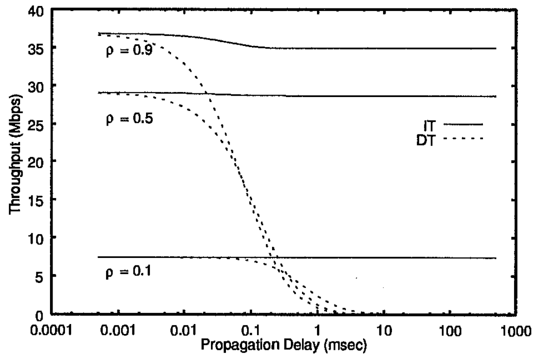


Figure 9: Throughput Comparisons of ABT/DT and IT dependent on Propagation Delay (Connection C1)

We next illustrate the effect of the requesting bandwidth, $b$, on the throughput of connection C1 in Fig. 10. The requesting bandwidth $b$ is varied as 150 Mbps, 75 Mbps, 50 Mbps and 37.5 Mbps, and the offered load $\rho$ is 0.9. From the figure, we can verify that performance tendencies of ABT/DT and IT are not affected by the amount of the requesting bandwidth. Same observation can also be made for other connections C2 and C3 as shown in Fig. 11.

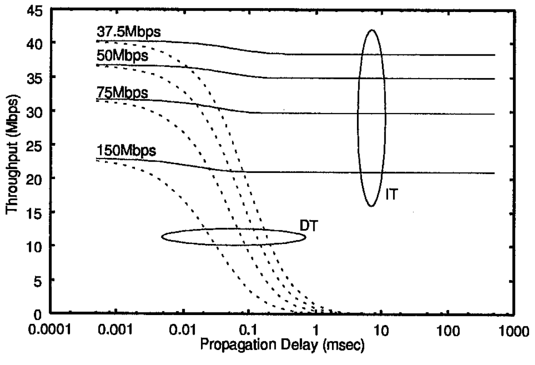


Figure 10: Throughput Comparisons of Bandwidths (C1, $\rho = 0.9$)

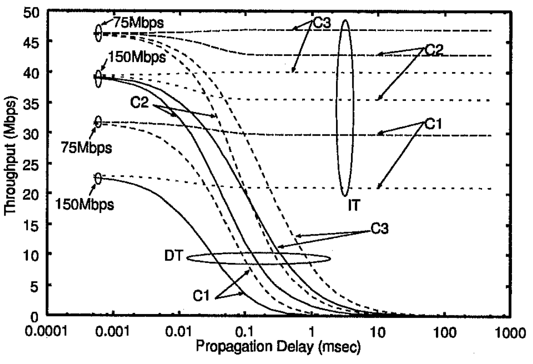


Figure 11: Throughput Comparisons of Connections ($\rho = 0.9$)

### 3.5. Application to the Random Network Model

In the previous subsections, we have treated a rather simple model depicted in Fig. 2. In this subsection, we examine more general network topologies. For this purpose, we generate random networks [21] with twenty nodes in 5 × 4 matrix. The link between two nodes is generated randomly. The connection between every two terminals is established with

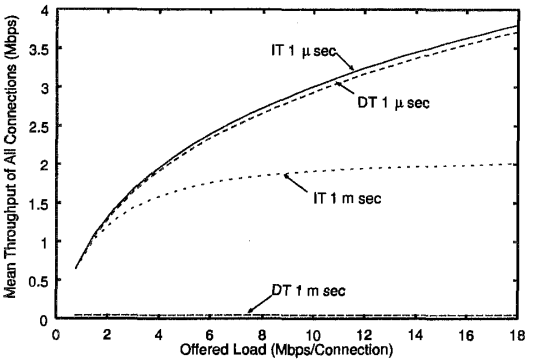


Figure 12: Effect of Offered Load in Random Network (Offered Load = 7.5 Mbps)

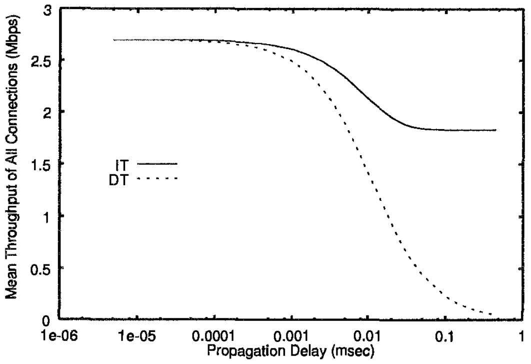


Figure 13: Effect of Propagation Delay in Random Network (Offered Load = 7.5 Mbps)

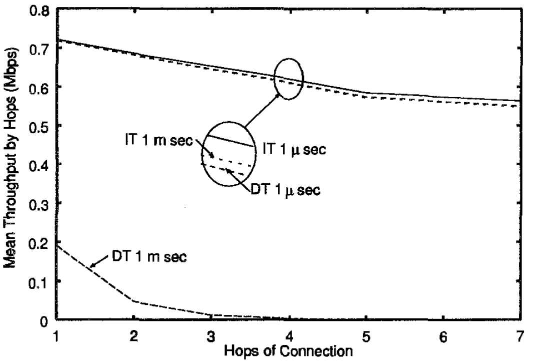


Figure 14: Effect of the Number of Hops on Throughput (Offered Load = 0.75 Mbps)

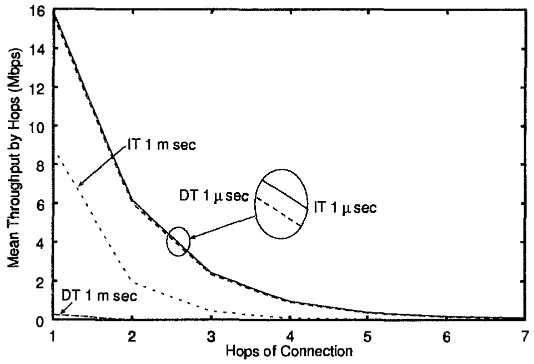


Figure 15: Effect of the Number of Hops on Throughput (Offered Load = 37.5 Mbps)

the shortest–path. If there are multiple shortest–paths with identical length, the path for connection establishment is chosen randomly.

Figure 12 compares throughputs of ABT/DT and IT against the offered load. As shown in the figure, we can observe the similar tendency as in Subsection 3.3, the performance of ABT/DT degrades dramatically by the larger propagation delays while that of IT does not. Throughputs of IT and DT against the propagation delay are compared in Fig. 13. We again observe the same tendency as in Subsection 3.4 even for random networks.

Next, throughputs of DT and IT are compared in Fig. 14 for two values of propagation delays; 1 $\mu$sec and 1 msec. The offered load of each connection is identically set to be 0.75 Mbps. In the figure, mean throughput dependent on the number of hops is plotted. As shown in the figure, the performance of ABT/DT is low and reaches almost zero as the number of hops becomes large while ABT/IT gives good performance independent of the number of hops. However, it is not true when the traffic load becomes high. As shown in Fig. 15, the throughput is suddenly decreased for connections with the larger number of hops even in ABT/IT.

## 4. Effects of Flexible Bandwidth Reservation Mechanisms

### 4.1. Effects of Bandwidth Negotiation in ABT/DT

In this subsection, we first consider the effect of the bandwidth negotiation mechanism which is only applicable to ABT/DT. By this mechanism, the blocking probability is expected to be decreased by accepting the reduced amount of bandwidth. More specifically, we consider the following bandwidth negotiation mechanism. Each source requests the bandwidth with an initial value, $b$, by using the forward RM cell. If the requested bandwidth $b$ is available on the link, the switch simply accepts the request. On the other hand, if the available bandwidth of the link is smaller than that value, the switch checks whether the half of the requested bandwidth is available or not. If it is available, the switch reserves the bandwidth of $b/2$ and overwrites it in the RM cell. If not, on the other hand, the switch again checks whether another half ($b/4$) is available or not. In this way, the bandwidth is reduced until the available bandwidth is found. When the switch receives the backward RM cell, it adjusts the reserved bandwidth to the one specified in the RM cell. Recall that such a negotiation cannot be implemented in ABT/IT since the burst is transmitted immediately following the RM cell. For evaluating the bandwidth negotiation mechanism, we use the model in Fig. 2. The initial requesting bandwidth $b$ is set to be 150 Mbps. In simulation, we set the minimum bandwidth to be 150/16 Mbps. Namely, if the available bandwidth on the link is less than 150/16 Mbps, the reservation request is rejected. It prevents the reserved bandwidth from being much less than the requesting bandwidth.

We first examine how the throughput of ABT/DT can be improved by introducing the bandwidth negotiation. Figure 16 shows the case of the short propagation delay, 1 $\mu$sec. As shown in the figure, the throughput of ABT/DT with bandwidth negotiation (labeled by "DT–R" in the figure) can be much improved. It becomes even larger than that of ABT/IT in which the bandwidth negotiation cannot be implemented. However, improvement is limited when the propagation delay becomes large as shown in Fig. 17, where the propagation delay is set to be 1 msec.

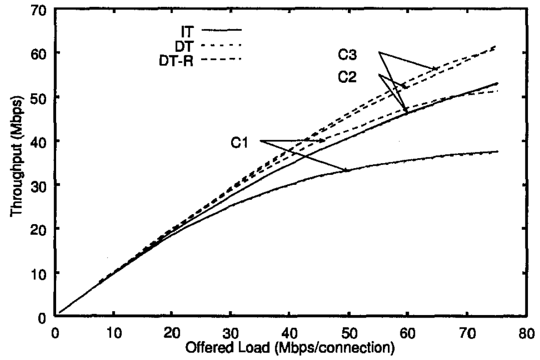


Figure 16: Effect of Bandwidth Negotiation in ABT/DT (Propagation Delay = 1 $\mu$sec)

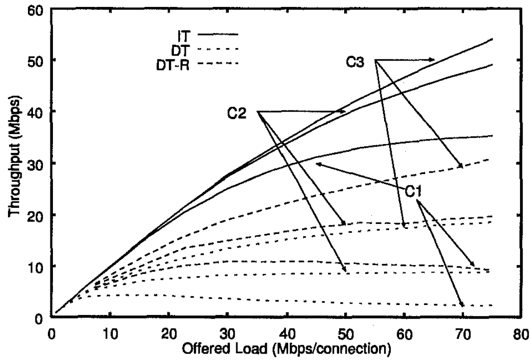


Figure 17: Effect of Bandwidth Negotiation in ABT/DT (Propagation Delay = 1 msec)

Improved performance in previous figures was obtained by reducing the reserved bandwidth. It implies that the burst transmission time becomes longer. We next use a *power* index, which is defined as a ratio of throughput to transmission delay. Here, the transmission delay is a time duration from burst generation at the source to its successfully reception at the destination. The results are plotted in Figs. 18 and 19 against the offered load for two values of propagation delays, 1 $\mu$sec and 1 msec, respectively. Figure 18 shows that the performance of ABT/DT with bandwidth negotiation is not good when we are concerned with the burst transmission delay. In other words, the effect of bandwidth negotiation in ABT/DT is meaningful in LAN environment if our main concern is only throughput. Otherwise, ABT/IT still gives better performance even in such a circumstance.

In the above experiments, we have assumed that the burst without successfully bandwidth reservation is lost. In the next subsection, we will investigate the case where the reservation request is repeated until it is successfully admitted.

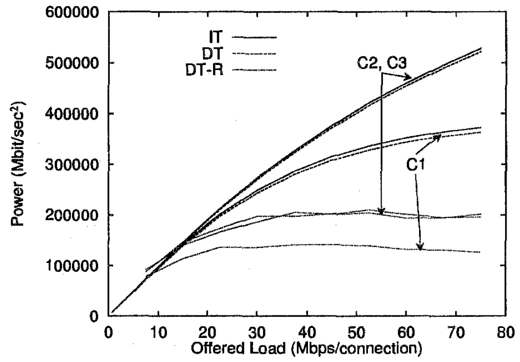


Figure 18: Effect of Bandwidth Negotiation in ABT/DT on Power (Propagation Delay = 1 $\mu$sec)

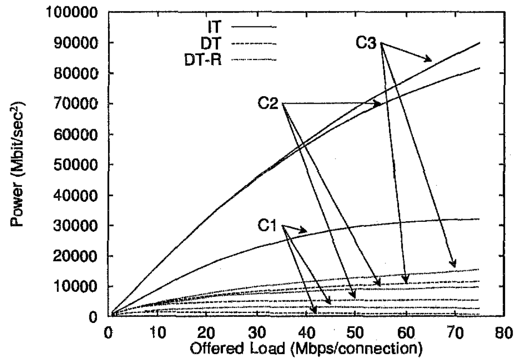


Figure 19: Effect of Bandwidth Negotiation in ABT/DT on Power (Propagation Delay = 1 msec)

### 4.2. Performance Comparisons of ABT/IT and DT with Backoff Methods

We last compare the performance by taking account of the backoff algorithm in both of ABT/DT and IT protocols. By the backoff, we mean that if the bandwidth reservation is rejected, the source waits during some time period (backoff interval) to retry reservation later. Since the reservation failure is an indication of congestion on some link of the route, the bandwidth reduction after the backoff could lead to the acceptance of the request. In [13], the authors compare several bandwidth reduction methods in ABT/DT, and concluded that the appropriate method is to reduce the requesting bandwidth to half after the reservation failure. In the current paper, we also consider such a bandwidth reduction method to compare ABT/DT and IT. In simulation, the following five methods are compared.

**Method M1:** ABT/DT in which the requesting bandwidth is always fixed even after the backoff.

**Method M2:** ABT/IT with fixed bandwidth for reservation as in Method M1.

**Method M3:** ABT/DT in which the requesting bandwidth is reduced to half after each backoff.

**Method M4:** ABT/IT, the bandwidth reduction method is same as Method M3.

**Method M5:** In the above four methods, the dynamic bandwidth negotiation mechanism in the previous subsection is not considered. In this Method M5, the requesting bandwidth is fixed even after the backoff, but the bandwidth negotiation presented in Subsection 4.1 is allowed for ABT/DT.

For the backoff time, we assume that it is distributed exponentially and its mean is set to be 300 $\mu$sec.

We first compare the burst transmission delays of Methods M1 and M2 in Fig. 20. The propagation delay is set to be short, 1 $\mu$sec. As shown in the figure, the difference of transmission delays between ABT/IT and DT is small. However, the burst transmission delay of ABT/DT becomes worse dramatically by the long propagation delay. As shown in Fig. 21 for the case of 1 msec propagation delay, it can easily be conjectured from the previous results of throughputs (Figs. 9 through 11).

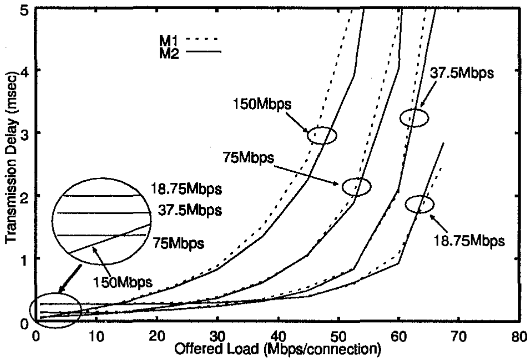


Figure 20: Transmission Delay dependent on Offered Load (Methods M1 and M2, Propagation Delay = 1 $\mu$sec)

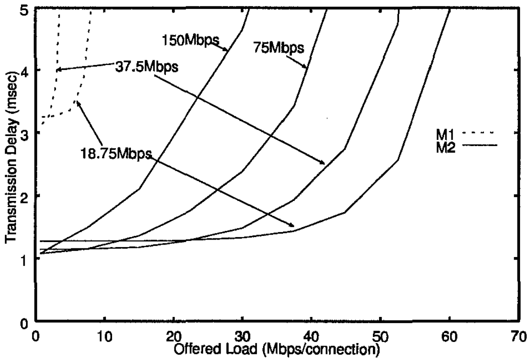


Figure 21: Transmission Delay dependent on Offered Load (Methods M1 and M2, Propagation Delay = 1 msec)

We now investigate the effect of bandwidth reduction after the backoff. Figure 23 compares Methods M2 and M4, i.e., ABT/IT with and without reduction of the requesting bandwidth. The propagation delay is 1 $\mu$sec. Initial bandwidths of Method M2 are varied as 150 Mbps, 75 Mbps, 37.5 Mbps and 18.75 Mbps. For Method M4, we only show the case where the initial bandwidth is set to be 75 Mbps. It can be observed that the performance of Method M4 is better than that of M2 in a sense that it can offer fairly good performance independent of the traffic load. It is because the reduced bandwidth of Method M4 leads to avoid the repeated backoffs as we expect. We can observe a similar result in the case of ABT/DT as shown in Fig. 22, where we compare Methods M1 and M3. In the case of long propagation delay, the similar results can be observed as shown in Fig. 24, where the propagation delay is set to be 1 msec.

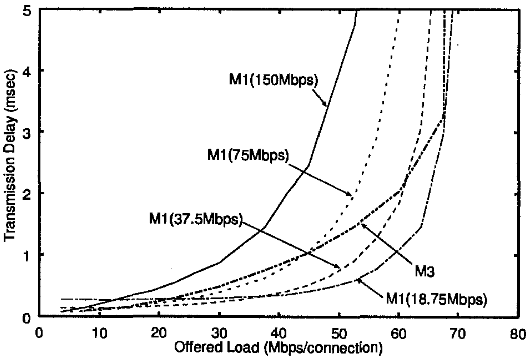


Figure 22: Transmission Delay Comparisons of M1 and M3 (Propagation Delay = 1 $\mu$sec)

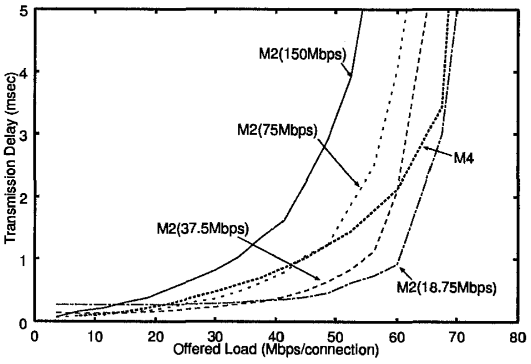


Figure 23: Transmission Delay Comparisons of M2 and M4 (Propagation Delay = 1 $\mu$sec)

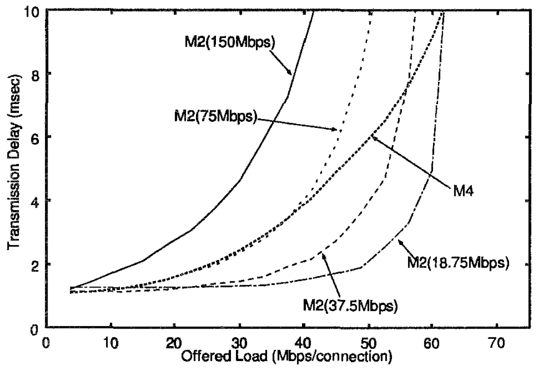


Figure 24: Transmission Delay Comparisons of M2 and M4 (Propagation Delay = 1 msec)

We next compare five methods in Figs. 25 and 26 with 1 $\mu$sec and 1 msec propagation delays, respectively. As can be found in Fig. 25, Method M5 gives best performance when the propagation delay is small. It is because in Method M5, the reservation is admitted even when a small amount of the bandwidth is available on the link, which can avoid backoffs. However, Method M4 (IT with bandwidth reduction) is most effective in the case of the long propagation delay because the overhead of ABT/DT introduced by the long propagation delay cannot be overcome even when the dynamic bandwidth negotiation mechanism is introduced.

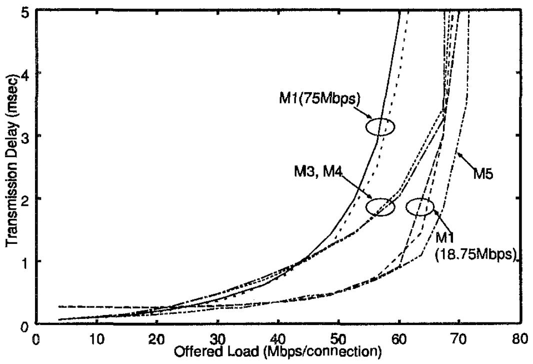


Figure 25: Transmission Delay Comparisons of Five Methods (Propagation Delay = 1 $\mu$sec)

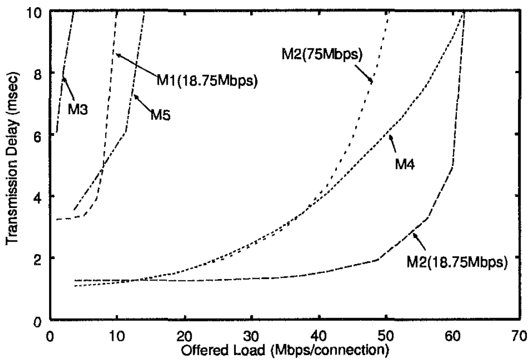


Figure 26: Transmission Delay Comparisons of Five Methods (Propagation Delay = 1 msec)

Last, the burst transmission delay comparisons of Methods M2, M4 and M5 dependent on the propagation delay are shown in Fig. 27. Method M5 outperforms other two methods if the propagation delay is small. However, as the propagation delay becomes longer than burst transmission times, the performance of Method M5 becomes worst suddenly. The same tendency was also observed in Subsection 3.4.

From the above experiments, we can see that Method M2 with a small reservation bandwidth exhibits a good throughput. However, it poses large transmission delays even when the traffic load is low. On the other hand, Method M4 (IT with bandwidth reduction) fairly gives a good performance in terms of both throughput and the transmission delay in all parameter regions we have tried.

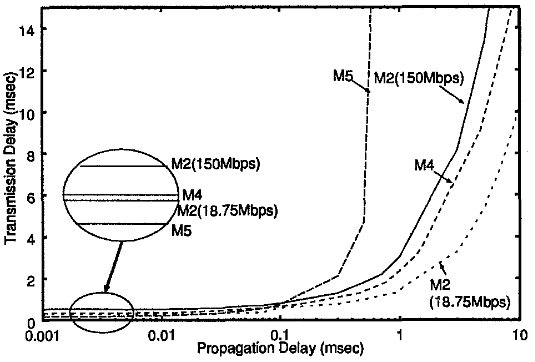


Figure 27: Transmission Delay Comparisons of M2, M4 and M5 dependent on Propagation Delay (Offered Load = 22.5 Mbps/Connection)

## 5. Concluding Remarks

In this paper, we have first investigated the basic performance of ABT/IT and DT. Then, we have shown that ABT/IT is robust in the sense that its performance is not heavily affected by the propagation delay. On the other hand, ABT/DT is quite sensitive to the propagation delay. We next considered the performance improvement by the bandwidth negotiation mechanism which is only applicable to the ABT/DT protocol. Simulation results have shown that it is effective in the short propagation delay case if our concern is throughput, but the burst transmission delay is still larger than that of ABT/DT. We have also investigated effects of backoff methods to compare the burst transmission delays, and have observed similar tendencies as in the above cases. In the case of the short propagation delay, ABT/DT with bandwidth negotiation is most effective. When the propagation delay becomes large, on the other hand, ABT/IT with reduced bandwidth mechanism outperforms other methods.

In Subsection 3.5, it was shown that performance of connections with the large number of hops is suddenly degraded even in ABT/IT. We need some mechanism to avoid such performance degradation as a future research topic.

## References

[1] ITU-T Recommendation I.371, "Traffic control and congestion control in B-ISDN," 1992 revised in 1995.

[2] The ATM Forum, "Traffic management specification version 4.0," *ATM Forum Contribution 95-0013R9*, December 1995.

[3] M. W. Garrett, "A service architecture for ATM: From applications to scheduling," *IEEE Network*, vol. 10, pp. 6–14, May/June 1996.

[4] H. Ohsaki, M. Murata, H. Suzuki, C. Ikeda, and H. Miyahara, "Rate-based congestion control for ATM networks," *ACM SIGCOMM Computer Communication Review*, vol. 25, pp. 60–72, April 1995.

[5] P. E.Boyer and D. P.Tranchier, "A reservation principle with applications to the ATM traffic control," *Computer Networks and ISDN Systems*, vol. 24, pp. 321–334, 1992.

[6] F. Guillemin and P. Boyer, "ATM block transfer capabilities: The special case of ABT/DT," in *Proceedings of IEEE GLOBECOM '96*, pp. 762–766, November 1996.

[7] I. Widjaja, "Random access for ATM LANs and WANs," *ICC '94*, pp. 39–43, 1994.

[8] S. S. Lam and G. G. Xie, "Burst scheduling: Architecture and algorithm for switching packet video," *Proceedings of IEEE INFOCOM '95*, pp. 940–950, 1995.

[9] S. S. Lam and G. G. Xie, "Group priority scheduling," *Proceedings of IEEE INFOCOM '96*, pp. 1346–1356, 1996.

[10] G. G. Xie and S. S. Lam, "Real–time block transfer under a link sharing hierarchy," *Proceedings of IEEE INFOCOM '97*, pp. 388–397, 1997.

[11] H. Shimonishi, T. Takine, M. Murata, and H. Miyahara, "Performance analysis of fast reservation protocols in ATM networks," *Performance Evaluation*, vol. 26, pp. 263–287, 1996.

[12] H. Shimonishi, T. Takine, M. Murata, and H. Miyahara, "Performance analysis of fast reservation protocol with generalized bandwidth reservation method," *Proceedings of IEEE INFOCOM '96*, pp. 758–767, 1996.

[13] H. Shimonishi, T. Takine, M. Murata, and H. Miyahara, "Performance analysis of fast reservation protocol in ATM networks with arbitrary topologies," *Performance Evaluation*, vol. 27&28, pp. 41–69, 1996.

[14] S.-P. Chung, A. Kashper, and K. W. Ross, "Computing approximate blocking probabilities for large loss networks with state-dependent routing," *IEEE/ACM Trans. on Networks*, vol. 1, pp. 105–112, 1993.

[15] F. P. Kelly, "Blocking probabilities in large circuit-switched networks," *Adv. Appl. Prob.*, vol. 18, pp. 473–505, 1986.

[16] F. P. Kelly, "Routing in circuit-switched networks: Optimization, shadow prices and decentralization," *Adv. Appl. Prob.*, vol. 20, pp. 112–144, 1988.

[17] F. P. Kelly, "Routing and capacity allocation in networks with trunk reservation," *Math. of Oper. Res.*, vol. 15, pp. 771–793, 1990.

[18] F. P. Kelly, "Loss network," *Ann. Appl. Prob.*, vol. 1, pp. 319–378, 1991.

[19] W. Whitt, "Blocking when service is required from several facilities simultaneously," *AT&T Tech. J.*, vol. 64, pp. 1807–1856, 1985.

[20] F. P. Kelly, "Reversibility and stochastic networks," *Jon Wiley & Sons, Chichester*, 1979.

[21] B. M. Waxman, "Routing of multipoint connections," *IEEE Journal on Selected Areas in Communications*, vol. 6, pp. 1617–1622, December 1988.

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