PERFORMANCE ANALYSIS STUDY OF MULTICAST TRAFFIC IN STAR-BASED LOCAL WDM LIGHTWAVE NETWORKS

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Abstract: Multicasting refers to a one-to-many network connection. Many-to-one and many-to-many connections are also categorized as multicasting. In a broadcast-and-select single-hop WDM network the only way to transmit information successfully is to have both source's transmitter and destination's receiver tuned to the same channel. The cost, scalability and efficiency issues of these approaches inspired researchers to study different ways in which the physical medium can be shared efficiently. In this paper, we study multicast traffic in single-hop local WDM optical networks based on a broadcast-and-select system. We use an approximate analytical solution to show the influence of tuning delay on the system performance under different network conditions. We also examine the effect of average packet delay on receiver throughput. Finally, we demonstrate the channel blocking probability versus network offered load characteristics.

1 INTRODUCTION

The emergence of wavelength division multiplexing (WDM) technology has been of particular significance because of its high-speed long distance transmission and vast transmission capacity, hence supporting multiple simultaneous channels on a single fiber. WDM optical networks are expected to be the backbone network for a bulk transport of traffic in the future broad-band networks. These wavelengths channels can operate at peak electronic speed, thus optically enabling an aggregate system capacity of several terabits/second. WDM also supports mechanisms such as multicasting at the physical layer without buffering (Modiano, 1999. Sue, 2002. Baldin, 2001).

WDM networks can be classified in two classes: broadcast-and-select and wavelength routed. In broadcast-and-select WDM network, a node sends its transmission to the star on one available wavelength, using a laser which produces an optical information stream (Mukherjee, 2000).

Communication between sources and destinations can be either single-hop or multihop. In single-hop systems, WDM is achieved by using lasers as tunable transmitters and optical filters as tunable receivers in order to provide switching between channels at high speeds. The hosts are directly connected to each other via direct two-way optical fibers to the passive star coupler (PSC). PSC is a piece of glass which works as a multiplexer for every incoming link by splitting the optical signal into all of the outgoing links and, in essence, broadcasting any input to all the outputs, hence the name broadcast-and-select. Its minimal bandwidth requirements make broadcast-and-select approach especially appealing for transmitting multicast traffic (Ramaswami 2002. Ramamurthy, 1998).

Multicast is the simultaneous transmission of information from one source to multiple destination nodes. Multicast can be supported more efficiently in optical domain by utilizing the inherent light splitting capacity of optical switches than copying data in electronic domain (Wang, 2002).

In single-hop WDM networks, the major issue is the coordination (scheduling) of the transmissions, because contentions may happen in such shared-media and shared-channel networks. One source of contention is so-called collision, when two or more transmitters want to transmit to the same wavelength channel at the same time. Another source of contention occurs when, in a system with tunable receivers, two or more transmitters want to transmit

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to the same destination node on different channels simultaneously. This situation is called a destination conflict (He, 2002).

A number of multicast scheduling algorithms (MSAs) for transmissions have been proposed. These MSAs can generally be classified as random-access-based MSAs, pre-allocation-based MSAs, and reservation-based MSAs.

In (Kitamura, 2001), some random-access-based MSAs are described. The system employs a centralized scheduler that operates in a slotted mode, maintains a request queue for each node, checks the request queues, and makes appropriate scheduling in each slot.

Preallocation-based MSAs are presented in (Tseng, 1998). These algorithms simply coordinate the transmissions according to some pre-determined schedule. The slots are preallocated for unicast purpose. In general, scheduling multicast transmissions is much more challenging than scheduling unicast transmissions, because the transmitter of the source node and the receivers of all the destination nodes in the multicast group need to be tuned to a common wavelength simultaneously. A multicast distance is used to determine whether the arrived multicast packet should be transmitted as a single multicast or multiple unicast packets. This information along with the multicast group of this packet is broadcast to all other nodes via a control channel. When the information for the multicast packet is received by all of the nodes, all of the nodes run the same scheduling algorithm to modify the preallocated slots to accommodate the multicast packet.

Reservation-based MSAs can be found in (Jue, 1997), where some partition schemes are proposed to address the problem of wasting the receiver resources. In particular, when the multicast group size is large, some receivers may have to wait for a long time without receiving anything because some other receivers in the same group are not available. Specifically, these MSAs allow a multicast transmission to be partitioned into multiple unicast or multicast transmissions and separate transmission is scheduled for each subgroup, in order to minimize the large receiver waiting time. Every node in the system model keeps track of the times beyond which each of the transmitters, receivers, and channels will be available.

For wide ranges of the traffic conditions and a wide range of the number of data channels in the network, a hybrid MSA has been proposed in (Lin, 2001). The proposed algorithm dynamically chooses to employ a MSA which always tries to partition multicast transmissions or a MSA which does not partition multicast transmissions depending on the average utilization factors of the data channels and the receivers.

The paper is organized as follows. Section 2 describes the system and traffic model. In Section 3, we use an approximate analytical approach to analyze the system performance in terms of average packet delay, receiver throughput and blocking probability. Section 4 presents some analytical results. Conclusion is given in Section 5.

2 SYSTEM DESCRIPTION

The system in study consists of a PSC with *N* nodes as shown in Figure 1. There are *W* channels,

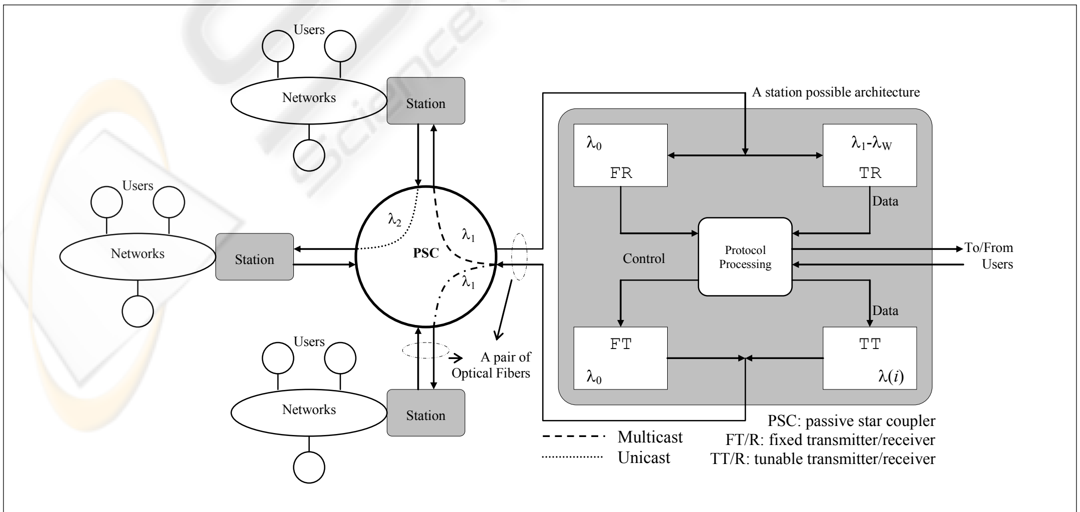

Figure 1: A broadcast-and-select star-based WDM system.

where $W \leq N$. Each station is equipped with a tunable transmitter and a tunable receiver. All stations can communicate with one another. In addition, a pair of fixed transceivers and control receiver both are tuned to the control channel is dedicated for pre-transmission co-ordination. However, communication between two nodes is possible only when the transmitter of the source node and receiver of the destination node are tuned to the same channel during the period of information transfer. Each node is connected to the PSC by a transmitting and receiving fiber, and each message is addressed (multicast) to a number of receivers l (destination set size), randomly chosen from the N nodes and each receiver tunes to one of the wavelength that has a message addressed to it.

Through multicasting, a source node is able to send a multicast message to multiple destination nodes in a single transmission, thus conserving the source transmitter's usage and bandwidth. Messages are transmitted repeatedly until received by all intended receivers.

It is shown in (Jia, 1993) that the main problems with MAC protocol for WDM optical networks are contention and destination collision. Therefore, to reduce the probability of destination collision a MAC protocol is designed to incorporates asynchronous transfer scheme to allow overlapping of one node's tuning time with other node's packet transmission time.

For example, a signal that originates on a particular channel remains on it until it reaches its destinations. Since, each node has a tunable transmitter and a tunable receiver and each of them can access any of the wavelength channels for transmission or reception, therefore, each channel in the network can be a copy of the network. These copies of the network operate independently in parallel with each other. The nodes on the other hand can transmit a multicast packet or receive it on as many copies of the network as the number of transmitter or receivers available to them.

3 SYSTEM ASSUMPTIONS AND ANALYSIS

The behavior of the system is characterized by the following assumptions:

- There are N nodes and W wavelength channels in the system.
- Each message is multicast to a set of l receivers where $l < W \leq N$.
- Whenever the receivers of a multicast group are ready to receive a data packet the source node's transmitter is ready to transmit.

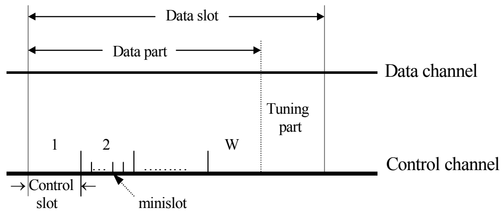

Figure 2: Control and data channel structure.

- A packet that arrives at the start of a slot can be transmitted during that slot to any one of the other $(N-1)$ nodes with equal probability.
- Random selection of a destination node among the $(N-1)$ nodes is renewed for each attempt of transmitting a control packet.

The system operates in a slotted mode with a time slot equals to the packet transmission time plus the tuning part as shown in Figure 2. Time on a control channel is divided into data slots. Each data slot is divided further into W control slots. Time on the data channel is synchronized with the time on the control channel. A control packet contains only the destination address and its transmission time is defined as one mini-slot. The transmission time for each control slot is equal to 1 unit.

3.1 System Performance

In this section, we analyze the system performance in terms of average packet delay and throughput. We first calculate the average delay a packet experiences. This delay is due to the data packet transmission delay, control channel delay, data channel delay, and propagation delay.

The length of data packet is fixed and equals to L control slots. Assume the receiver tuning time is T_r control slots. Thus, the data packet transmission delay equals to

$$D_d = L + T_r . \quad (1)$$

Assume the arrivals are Poisson of rate A per control frame. The server process is deterministic with rate $\mu = 1$ per control frame, and the offered load $a_c = A/\mu$. Therefore, the average delay a data packet incurred before its corresponding control packet is sent can be given by

$$D_c = 1 + W/2 + a_c / 2(1-a_c) . \quad (2)$$

When the receivers of a multicast packet are ready to receive a packet, a free channel is available for transmission. If the number of free channels is few, a free channel may not be available and the packet may be delayed. Thus, the offered load can be given as $a_{ch} = A(D_d)/W$. Therefore, the delay due to the data channel can be calculated as

$$D_{ch} = a_{ch} / 2W(1 - a_{ch}) \,. \tag{3}$$

The total propagation delay between any node in the system and the passive star coupler is R and is assumed to be the same for all the nodes. Thus, the propagation delay for a data packet is $D_R = 2R$.

Note that the average packet delay is measured from the time the packet is generated at the node until it is completely received by the destination. Therefore, the average packet delay can be given by

$$D = \frac{1}{aW} + \frac{N}{S} + \frac{2T + W}{W} \tag{4}$$

where $1/\alpha W$ is the average time the packet stays waiting for generation (idle state), N/S is the average waiting time the packet experiences from the moment it enters the idle state to the moment it returns to it, S is the system throughput, and T is the transceiver tuning time.

At the maximum offered load, we obtain

$$D = \frac{1 + 2R + 2T + W + 1/p}{W} \tag{5}$$

where $1/p$ is the average time a node waits before it transmits its control packet in a current control slot.

We now can obtain the achievable throughput of the system as follows:

$$\frac{1}{S} = \frac{D}{N} + \frac{1}{\alpha WN} + \frac{2T + W}{WN} \tag{6}$$

$$S = \frac{1/W + a + 1/N}{(a+1)D + 1/W + 2 + 2aT + aW + 2T/W} \tag{7}$$

At the maximum offered load, we have

$$S = \frac{1 + (W+N)/2}{R + 4TWN + 2W^2N + N/2 + WN + WNT + W^2N/2 + NT} \,. \tag{8}$$

3.2 Multicast Transmissions

The analysis that follows assumes that a new message arrives at the beginning of a time slot only when transmission of a previous message is completed at the end of the previous slot. A new message is destined to node i with probability l/N. If we now let $Q^i{}_m$ be the number of messages addressed to node i at the end of m^{th} time slots, and since node i can only receive one message during any time slot, we the have

$$Q^i{}_m = \max(0, \quad Q^i{}_{m-1} + \alpha^i{}_m - 1) \tag{9}$$

where $\alpha^i{}_m$ is the number of new messages arriving and destined to node i.

When the arrivals are Poisson of rate A, the average number of messages destined to a receiver can be expressed according to the M/D/1 queue system by

$$Q = A + \frac{A^2}{2(1-A)} \,. \tag{10}$$

Since there are N nodes, each node has lW/N transmissions intended for it and it only receives one transmission at a time $\overline{T}$, the average number of transmissions required by a message can be given as lower bounded $\overline{T} > \max(W/N, 1)$. When $lW < N$ the system is channel limited, i.e., there are not enough channels to keep all the receivers busy, the receiver cannot be fully utilized because messages will have to be retransmitted many times. When $lW > N$ the system is receiver limited, i.e., number of receivers is too small to keep all the channels busy with new transmissions.

Let M_{max} be the number of messages waiting in the transmitter queue and let Q_{max} is the maximum number of messages waiting in the queue, then the number of new arrival messages can be obtained as

$$A_{max} = M_{max} - Q_{max}. \tag{11}$$

In a slotted system, if there are new arrivals to the queue during a slot, half of these new arrivals will be placed ahead of the given message in the queue and half behind it. Hence, if $\overline{\alpha}_n$ is the average number of new arrivals to the queue, the average waiting time in the queue can be given by

$$\overline{T} = 1 + 2T + \overline{Q}_{\max} + \frac{\overline{a}_n}{2} \,. \tag{12}$$

However, if the arrival rate is greater than unity, $\overline{T}$ will be infinite and S will be zero. Since the transmission takes place on W wavelength channels, the average number of completed multicast transmissions per time slot is $\overline{T}/W$ and the average arrival rate can be given by

$$\overline{\alpha}_n = Wl / N\overline{T} \,. \tag{13}$$

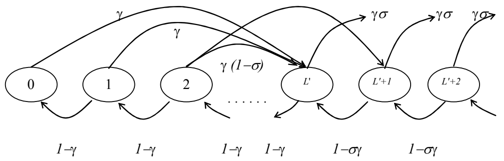

Figure 3: Markov chain transition probabilities.

It is shown in (Laxman, 1997. Modiano, 1999) that when the number of nodes with receiver busy time is equal to the multicast size, the behavior of the system could be described using an approximate Markov chain model shown in Figure 3, where σ represents the probability that the receiver is busy, and γ is the arrival rate of data packets per control slots. The maximum receiver busy time over all the nodes is assumed to be B_{Rmax}. If a node has receiver busy time less than B_{Rmax}, the receiver busy time equals to $B_{\mathrm{Rmax}} - (L + T_r) = L'$. The probability that the value of B_{Rmax} increases is given by σ and the probability that a multicast packet is transmitted in a current slot is given by γ. If $B_{\mathrm{Rmax}} = 0$ or 1, the value of B_{Rmax} approaches L'. Therefore, there is only one forward transition from state 0 and from state 1 to state L'. For $B_{\mathrm{Rmax}} < L'$, the receiver busy times of the nodes will either equals to B_{Rmax} or zero.

Therefore, there are two possible probabilities. The first is ($\gamma\sigma$) if at least one node participating in the multicast has receiver busy time equals to B_{Rmax}, and in this case the next state is $B_{\mathrm{Rmax}} + L' - 1$. The second is $\gamma\,(1-\sigma)$ if all the nodes in the multicast have receiver busy time equals to zero, and in this case the next state is L'.

3.3 Channel Blocking Probability

Channel blocking probability is defined as the probability that there is no sufficient capacity for a channel in a finite link. For a finite buffer case, the system throughput equals the arrival rate multiplied by (1 - blocking probability) (Vastola, 1997).

In the following we make the assumption that the multicast size has a uniform distribution. The throughput is then limited by a form of blocking results from a channel being efficiently used while the message being transmitted on that channel is waiting for receivers to become available.

Now consider a single channel λ_i using $W_{i,on}$ and $W_{i,off}$ to denote the mean *on* and *off* periods in a finite system, respectively. Hence, the blocking probability of channel i can be given by

$$P_B = \frac{\lambda_i \overline{T}_{i,off} - 1}{\lambda_i \overline{T}_{i,on} + \lambda_i \overline{T}_{i,off}} \tag{14}$$

where the numerator denotes the mean number of failed attempts to subscribe to W_i during a time slot and the denominator represents the mean total number of attempts during a time slot. When the channel is *off*, we have

$$P_B = (1/\lambda_i \overline{T}_{i,off}) - 1\,. \tag{15}$$

The request for connection between any two users will be blocked if there is no wavelength which is available on every link between them. We assume that a node will select one message randomly when there are many transmissions to choose from. This means during each slot, W messages are chosen for transmission from among N nodes.

Let C be the average duration of a connection, and λ_i is the arrival rate on the i^{th} link of the path. The average offered load on the i^{th} link of the path α_i is then $C\lambda_i$. Thus, the probability that all the W channels are busy on that link connecting source and destination which represents the probability of blocking is finally obtained as

$$P_B = \frac{(C\lambda_i)^W}{W!} = \left(\alpha_i^W \middle/ W \right) \Bigg/ \sum_{j=0}^{W} \alpha_i^W \Big/ j!\,. \tag{16}$$

4 RESULTS

The effect of tuning time on average packet delay is shown in Figure 4. Note that when T increases the packet delay gets larger but the system throughput does not change because there is enough bandwidth available to accommodate all of the traffic demand. With larger T, the maximum throughput of system stops at a lower value when $\alpha = 1$ since more states in the system are waiting for transmitting or receiving packets.

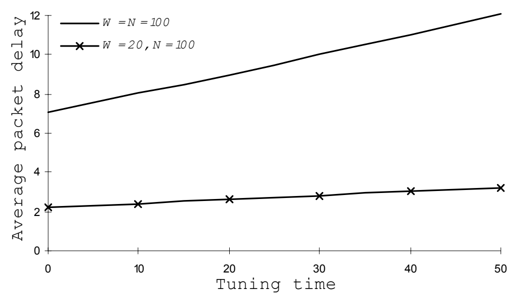

Figure 4: Average packet delay vs. tuning time.

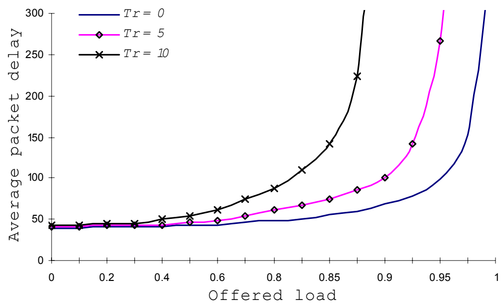

Figure 5: Average packet delay vs. offered load.

Figure 5 examines the average packet delay versus offered load characteristics of a system with N = 100, W = 20, propagation delay is 10, receiver tuning time is 0, 5, and 10, transmitter tuning time is zero, and the offered load varies from 0 to 1. When the offered load is high (1 > α > 0.8) the average packet delay increases significantly since the available channels will not be enough to accommodate large number of packets that are transmitted by the users.

In Figure 6, we demonstrate the average packet delay versus number of wavelengths characteristics. We can observe that for a same number of wavelengths and average waiting time for a node, the average packet delay is very small for a system with zero tuning time and zero propagation delay compared to a system with T = R = 10 control slots. The maximum packet delay occurs when number of wavelengths is small.

Figure 7 examines the effect of the average packet delay on receiver throughput. Note that when the destination group size is small the receiver throughput is large since the mean number of nodes with receivers busy is relatively small as the mean number of receivers required by the new messages that enter the system. The probability that a new message can find the particular receiver it requires for its particular multicast connection is high.

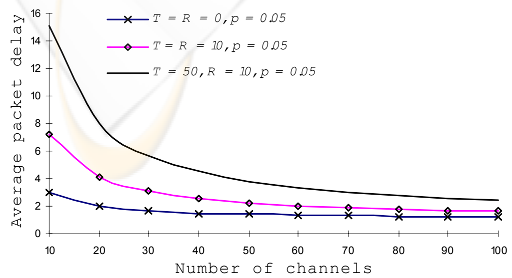

Figure 6: Average packet delay vs. number of channels.

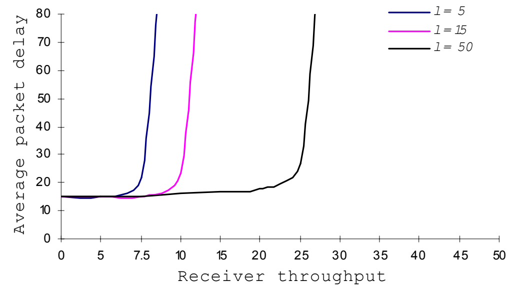

Figure 7: Average packet delay vs. receiver throughput.

Figure 8 demonstrates the receiver throughput versus receiver tuning delay characteristics for a system with 50 nodes and 10 channels. The probability that the number of nodes with busy receivers is assumed to be 0.5 and 0.8 and the system has a constant multicast size equal to 5 and 15 respectively with packet length equal to 10.

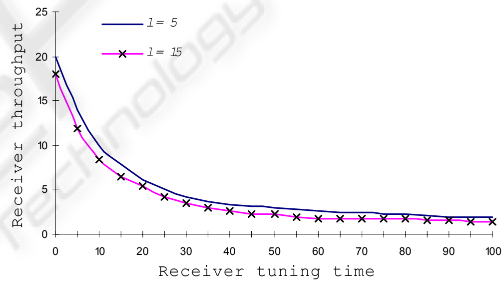

Figure 8: Receiver throughput vs. tuning time.

In Figure 9, we evaluate the system performance in terms of channel blocking probability against offered load for a system with 100 nodes and a different number of channels. Note that for a same load, the maximum blocking probability decreases

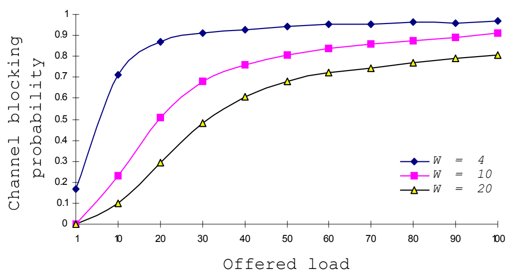

Figure 9: Channel blocking probability vs. offered load.

as the number of channels increases. This is because when the number of channels in a system increases, the probability that every user in the system will find an available channel also increases.

5 CONCLUSION

The system can accommodate large tuning delays and keeps with suitable throughput when the number of wavelength is equal to the number of nodes. When the number of wavelengths is comparable to the number of users the tuning time influence on the packet delay increases. The multicast performance may be improved by allowing the new messages to be transmitted while the old messages are waiting to be retransmitted. Alternatively, nodes select the message they receive which transmits multiple times to the same destination simultaneously. When the system is examined under uniform distribution of multicast set size, the throughput efficiency is higher for a system with a small number of wavelengths compared to a system with a large number of wavelengths. When the system has many receivers per message, it requires all those receivers to be available as the transmission takes place and hence, with a small multicast size the probability that this requirement can be satisfied is bigger.

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