A Bandwidth Guaranteed Multi-access Protocol for WDM Local Networks

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Abstract— *In this paper, we propose a bandwidth guaranteed multi-access protocol for broadcast-and-select WDM local networks with a star topology. The proposed protocol is based on a combination of contention and reservation mechanisms for time slotted WDM networks. Every node accesses the data channel by transmitting request packets in minislots on a separate control channel. There are two types of minislots; reservation minislots and contention minislots. Nodes requiring bandwidth guarantees, called guaranteed nodes, use reservation minislots, that are assigned by the control node. The remaining nodes share contention minislots using a random access mechanism. Each node dynamically assigns data channels for the minislots successfully returned on a First-Come-First-Served (FCFS) basis. Here, the number of reservation minislots is allocated by the control node. The remaining minislots are used for contention minislots. The reservation minislots can guarantee a minimum bandwidth for the guaranteed nodes. The contention minislots enable on-demand services at the optical layer and achieve good fairness for the remaining bandwidth. This protocol can be implemented with a simple distributed algorithm that efficiently utilizes the data channel.*

Keywords— **Multiple access protocol, Bandwidth Guaranteed, QOS, WDM local network, Contention and reservation protocol**

I. Introduction

The advancement of semiconductors and optical technologies in the past decade has revolutionized communication networks. Particularly, optical fiber is being used as a replacement of copper wire cable in telecommunications due to its well known superior characteristics such as large bandwidth, very low error rate and low cost [1]. For example, a single-mode fiber has a bandwidth of about 30 THz in the low-loss region of 1.3 μm to 1.6μm.

However, electronic devices cannot utilize the whole bandwidth, since they can only handle bit rates up to a few *Gbps*. Nevertheless, it is difficult to lay new fibers in order to accommodate the increasing bandwidth requirement. One way to overcome the electronic bottleneck without laying new fiber is to use the wavelength division multiplexing (WDM) technology. WDM is a means to carve up entire optical bandwidth to multiple non-interfering wavelength ranges. Each wavelength is independently accessed by electronic devices and the entire bandwidth is utilized through either shared or dedicated access. Today, optical networks are mainly backbone or physical layer networks. However, optical networks in the form of all-optical networks are becoming transport networks, that can directly accommodate high level network services.

Broadcast-and-select WDM network is a good solution for all-optical local area networks. Distributed supercomputing, cluster computing and broadcasting studio applications impose critical requirements on WDM networks [15]. This is because diverse premise equipment can be directly interconnected to the network. Various traffic types that directly handled by end system equipments, such as, circuit switched, packet switched, and so on, can be simultaneously exchanged. The provision of a wide variety of services can be supported, where applications with different quality of service (QOS) requirements can coexist [4].

Several multi-access protocols and architectures for broadcast-and-select WDM local area networks have been proposed in the literature [2],[8],[9],[14]. Recently proposed access protocol can achieve high wavelength utilization up to 100% [10]. However, so far, most efforts have been focused on protocols for just one generic traffic type. Thus, bandwidth guarantee in multi-access protocols is becoming an important issue for WDM local networks. Although some recent proposals present bandwidth guaranteed algorithms to accommodate real-time multimedia services, the main focus was on scheduling algorithms for given traffic type [5],[6]. So far, no random-access protocols that can guarantee minimum bandwidth have been presented.

In this paper, we propose a contention and reservation protocol that provides on-demand services as well as bandwidth guaranteed services at the optical layer. The protocol can guarantee minimum bandwidth. The remaining bandwidth is fairly shared by all nodes. Moreover, the data channels are efficiently utilized. The protocol is implemented with a distributed algorithm based on contention and reservation mechanisms.

The remainder of this paper is organized as follows. In Section II, we describe the network architecture and the proposed protocol. In Section III, we analyze the throughput for each node via simulation. A conclusion is provided in Section IV.

II. The Proposed Multi-access Protocol

A. Network Architecture

Fig. 1 shows the network architecture being considered in this paper. It is a broadcast-and-select WDM local area network where every node interconnects with a passive star coupler as a star topology. There are M access nodes and one control node (i.e., $M+1$ nodes). The usable bandwidth is divided into $N+1$ wavelengths, $\lambda_0, \lambda_1, \cdots, \lambda_N$. The wavelength λ_0 is dedicated to the transmission of control information. The other N wavelengths are dedicated to the transmission of data traffic. In what follows, we associate each wavelength with its corresponding channel.

Each node has a FT-FR-TT-TR structure, that is a fixed-transmitter, a fixed-receiver, a tunable-transmitter and a tunable-receiver. In Fig. 1, the fixed- and tunable-transmitters are on the left of the star coupler, and the fixed- and tunable-receivers are on the right. Fixed transceivers (transmitters and receivers) are locked on the control channel, λ_0 . But tunable transceiver can tune to any wavelength, λ_i within the range of N data channels and send/receive information on the channel, simultaneously.

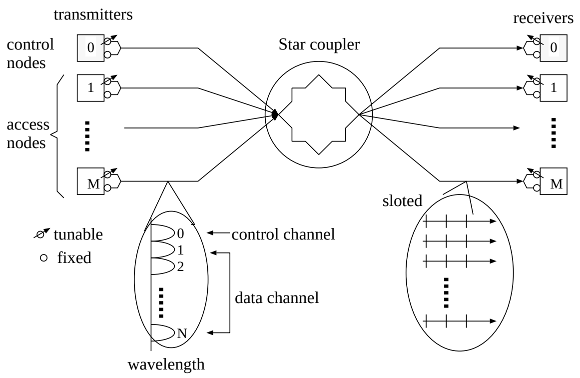

Fig. 1. Network architecture.

Fig. 2 shows a typical channel structure over time. All optical links are slotted with time slot, T_s. The transmission time of data and control packets are synchronized at the beginning of each slot. In this figure, the first horizontal line, represents the control channel λ_0. The other N lines represent the data channels. Also, T_r is the size of the reservation information region and T_m is the size of the minislot. m is the number of minislots.

Figs. 3 and 4 show data and control slot structures in details. As depicted in Fig. 3, the data packet size is fixed although it may be less than the slot size. This is because the tuning latency is included in a slot time and it is concatenated to the transmission time of a data packet, T_d. Although the tuning time is dependent on the device technology, we assume that it is negligible ($T_d \simeq T_s$) [5].

The size of a control slot is also fixed to that of a data slot, T_s. But, the control slot is further divided into a reservation information and m minislots. The reservation information consists of X bits. Each bit is dedicated to a guaranteed node through a connection control mechanism, which gives the reservation status of the corresponding guaranteed node. The maximum number of guaranteed nodes is limited to the number of bits, X. Moreover, the size of the reservation information can be very small compared with the slot length, since the reservation information is a bit pattern. In this paper, therefore, we can assume that the overhead of the reservation information is small compared to the portion of the minislots.

The number of minislots, m is defined by

$$m = \lfloor \frac{T_s - T_r}{T_m} \rfloor, \tag{1}$$

where $\lfloor z \rfloor$ indicates the largest integer not greater than z. There are two types of minislots; reservation minislots and contention minislots. The reservation minislots are used for the guaranteed nodes. The contention minislots are shared by all other nodes. The number of reservation minislots, m_r is variable. It is dynamically allocated by the reservation information which is managed by the control node at every slot. The remaining minislots, $m_c (= m - m_r)$ are used for contention minislots. Each minislot delivers a request packet that consists of a source address, destination address and queue status. The source address represents the node sending the request packet. The destination address represents the destination node for the request packet. The queue status is reserved for future usage.

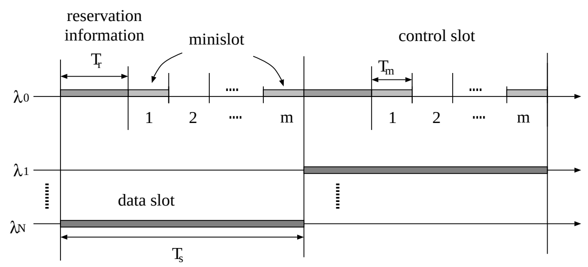

Fig. 2. Data and Control Channel structure.

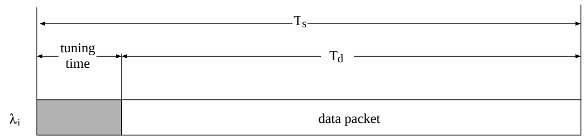

Fig. 3. Data Slot structure.

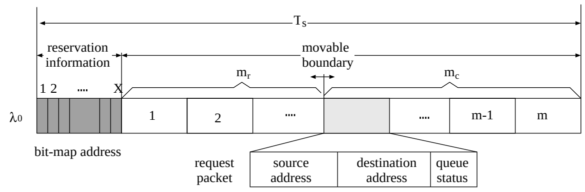

Fig. 4. Control slot structure.

Let's consider the round-trip delay between a transmitter and a receiver. The round-trip delay is equal to the end-to-end propagation delay, τ. Usually, the propagation delay is negligible since electric propagation speed is much faster than the data rate. However, in optical networks, the data rate is considerably higher and approaches the optical propagation speed [15]. In this case, the propagation delay is not negligible. Fig. 5 shows two examples of the propagation delay, where we assume that the network diameter is $2Km$ and the packet size is 8000 bits. In case (a), we assume that data rate is $10Mbits/s$. In case (b), we assume that data rate is $1Gbits/s$. In the former case, τ is $\frac{2^3}{2\times10^8} = 10\mu sec$, where the electric propagation speed is assumed to be $2 \times 10^8 m/s$. T_s is $\frac{8000}{10\times10^6} = 800\mu sec$. The propagation delay is negligible compared with the packet transmission time. However, in the latter case, τ is $\frac{2^3}{2\times10^8} = 10\mu sec$, where the optical propagation speed is assumed to be $2\times10^8 m/s$. T_s becomes $\frac{8000}{1\times10^9} = 8\mu sec$. Thus, the propagation delay is closed to the packet transmission time. Depending on the data rate, the end-to-end propagation delay is an important consideration in the design of a multi-access algorithm. Thereby, the propagation delay should be considered in designing multiple access protocol for WDM networks.

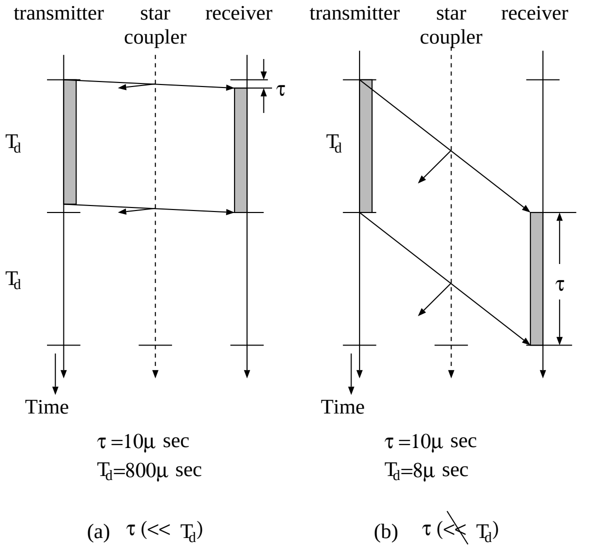

Fig. 5. Various end-to-end propagation delays in the network.

B. Protocol

In the protocol described below, we assume that the guaranteed nodes have established a connection with the control node. When the connection is established, the control node assigns an available bit in the reservation information, and maintains each bit according to the reserved bandwidth. The control node guarantees the reserved bandwidth by marking the corresponding bits in the reservation information (called reservation marks). The frequency of the reservation marks indicates the reserved bandwidth.

Fig. 6 shows the flow diagram of the proposed protocol. It consists of three procedures; the reservation, the pre-transmission and the transmission control procedures. In this figure, (a) shows the transaction flow between the control node and the access nodes in the reservation control procedure, and (b) and (c) show the transaction flow between the access nodes in the pre-transmission and transmission control procedures, respectively.

In the reservation control procedure, the control node sends reservation information an every slot by marking bits

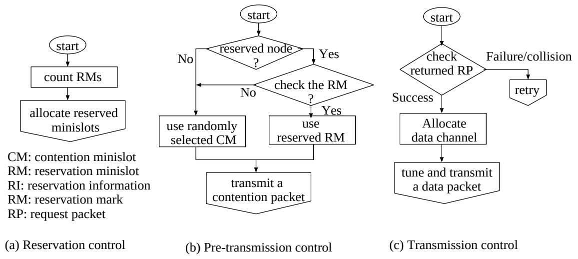

Fig. 6. Flow diagrams of the proposed protocol.

according to the reserved bandwidth. Upon receiving the reservation information, each node checks the reservation marks, and allocates minislots (called reservation minislots) as much as the number of reservation marks (see (a)). Each marked bit corresponds to a reservation minislot. The order of the reservation marks indicates the position of the reservation minislots: first reservation minislot is associated with the first reservation mark, the second one is associated with the following reservation marks, and so on. The remaining minislots are used for the contention minislots.

In the pre-transmission control procedure, each node that has a packet to be sent chooses one minislot and transmits a request packet. In case the node is a guaranteed node, the node uses the reservation minislot that is allocated to it in the reservation control procedure. If the reservation information bit is not marked, the node must wait until the reservation information bit is marked. Otherwise, the other node randomly selects a minislot among the contention minislots using the slotted ALOHA mechanism (see (b)). When minislots have been selected, every node transmits a request packet in the minislot. Reservation minislots do not incur any collision since each is dedicated to one guaranteed node for the given slot. However, collisions may occur in contention minislots when two or more nodes choose to transmit the same minislot.

After a round trip delay, all nodes receive the returned request packets and process them according to the transmission control procedure (see (c)). Without discrimination for the type of minislot received, each node runs the same transmission control procedure on a FCFS-basis. First, the node examines the optical level of the minislot received. From the optical level, the node can check the optical collision of the request packet. Next, the node examines the destination address to the addresses received. This address examination can eliminate the receiver collision with the request packets arrived before, since some nodes may transmit request packets to the same destination. If a request packet is collided due to the optical collision or destination conflict, the node retries the control procedure at the next slot. If a request packet is successfully returned without any collision, a data channel is sequentially allocated. The order of the successfully returned request packets indicates the address of the data channel: first data channel is associated with the first successfully returned request packet, the next one is associated with the next successfully returned request packet, etc. When the data channels are assigned, the source nodes tune their transmitters to the data channels to transmit their data packets on the data channels. The destination nodes also tune their receiver and receive the data packets after a round-trip delay.

Let's show an example of the control procedure. In this example, we assume that $M = 10$, $X = 6$, $m = 5$, and $\tau = 1$. Reservation information bits 1, 3, and 5 are assigned to reserved nodes 6, 2, and 3, respectively. Fig. 7 shows the reservation control procedure. The control node sends the reservation information at every slot as shown in the figure. In slot $k-1$, the control node sends the reservation marks in bits 1 and 3. Upon receiving the reservation information, each node counts the number of reservation marks, and allocates two minislots, 1 and 2 (called the reservation minislots) for the guaranteed nodes in slot k. The difference between k and $k+1$ is caused by the propagation delay. The guaranteed nodes, 2, 3, and 6 further check the specific bits, 3, 5, and 1 in the reservation information, respectively. From the results, guaranteed node 6 and 2 know that the first minislot is dedicated to guaranteed node 6 and the second one is dedicated to guaranteed node 2. The remaining minislots, 3, 4, and 5 (called the contention minislots) may be accessed by other nodes in contention. In slot $k+1$, this procedure is repeated. Then, minislot 1 is dedicated to guaranteed node 3 in $k+2$. The remaining minislots, 2, 3, 4 and 5 may be accessed by other nodes via contention mechanism.

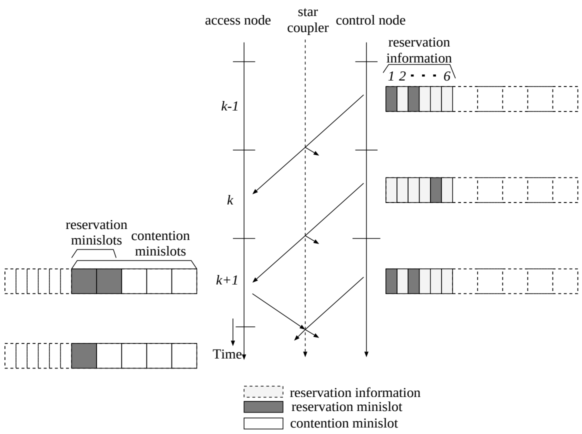

Fig. 7. An example of reservation control procedure.

Fig. 8 shows the pre-transmission and the transmission control procedures. Since bits 1 and 3 are marked in slot k, nodes 6 and 2 are allowed to use reservation minislots 1 and 2 in slot $k+1$ according to the reservation control procedure. On the other hand, the remaining nodes may select minislots among contention minislots 3, 4, and 5. In this example, it is assumed that node 1 randomly selects minislot 4 among contention minislots 3 to 5. In slot $k+1$, node 1, 2, and 6 transmit a request packet in minislots 4, 2, and 1 through the transmission control procedure, respectively.

After a round-trip delay, in slot $k+2$, every node receives the returned request packets, one-by-one, and runs the transmission control procedure. Since the request packet

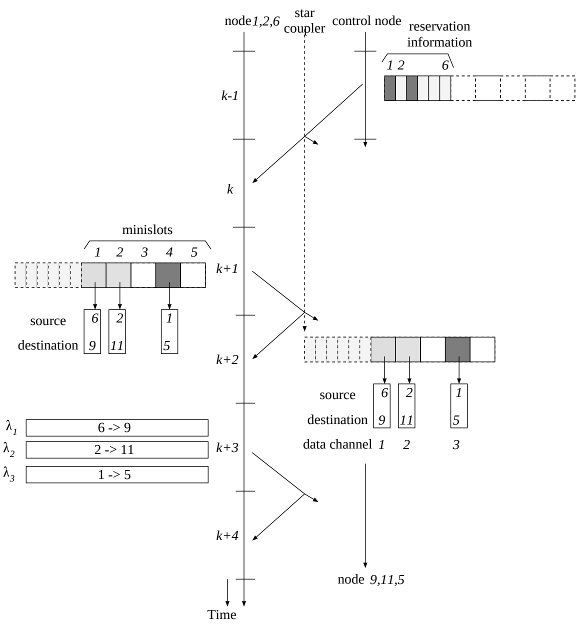

Fig. 8. An example of pre-transmission and transmission control procedures.

on minislot 1 is successfully returned, data channel 1 is assigned to the request packet. It means that node 6 sends a data packet to node 9 on data channel 1 in slot $k+3$. Similarly, data channel 2 is assigned for the second request packet on minislot 2 and data channel 3 is assigned for the third request packet on minislot 4. Consequently, in slot $k+3$, nodes 1, 2 and 6 tune their transmitters to data channel 3, 2, and 1, and send data packets to node 5, 9, 11. After a round-trip delay, nodes 5, 11, and 9 also tune their receivers to data channel 3, 2 and 1 to receive the data packet.

The proposed protocol is a simple distributed algorithm based on a contention mechanism. The control node repeatedly sends reservation information followed by m minislots. Wile transmitting reservation information, the control node only manages the reservation marks according to the reserved bandwidth. Every access node uses the data channel through the pre-transmission of a request packet without maintaining any reservation history called global information [10]. The request packets will be transmitted on the minislots. Guaranteed nodes use reservation minislots and the other nodes use contention minislots. The reservation minislots carry request packets without collision, but the contention minislots are subject to collision. Data channels are dynamically allocated based on the successful return of request packets on a FCFS basis.

This protocol only shows the possibility of the bandwidth guaranteed protocol in WDM local networks. It does not describe any specific implementation. For implementing protocol, therefore, various schemes can be designed. We can conceive measurement-based or on-demand schemes for managing the reservation marks. In fixed scheme, the control node sends the reservation marks at fixed interval. In the measurement scheme, the control node checks the usage of the reservation marks and regulates the frequency of reservation marks. In on-demand scheme, the reservation marks can be directly controlled by the guaranteed nodes. Although the last one provides the best performance, it requires accurate bit-by-bit synchronization at the optical layer. It may be applicable once the optical technology is mature. Therefore, in what follows, we only consider fixed allocation scheme. The other variations for variable-length packet and asynchronous protocol are remained further studied areas.

III. Performance Results

In this section, we verify the performance of the proposed protocol with computer simulation. The following performance result does not reflect an optimal solution. Instead, this result shows some performance examples as a proof of the protocol. In the results, the offered load, p is defined as the probability that a packet is generated when a node is in empty. p has a value from 0 to 1. Throughput is defined as the number of packets transmitted per a slot. For a node, throughput can be 0 to 1. For the entire network, throughput may have a value from 0 to the number of data channels, N ($N > 1$) (i.e., throughput for the entire network may be greater than 1). This is because WDM network can provide multiple data channel, concurrently.

In the simulations, we assume that each node contains a single buffer [10] and it belongs to either the idle or the backlogged states. Only idle nodes can generate a new packet with probability p. Backlogged nodes can not generate new packets, but retransmit old ones with probability 1. The destination of new arrivals and backlogged packets is selected among M nodes with uniform distribution. There is no loss in the node [9]. The other parameters are set as follows. $M = 50$ ($M_G = 10$, $M_U = 40$), $N = 5$, $m = 10 - 20$, $\tau = 0 - 4$, and $X = 10$. Node 1 and 2 reserve one slot every two slots (0.5 $packets/slot$), node 3 and 4 reserve one slot every four slots (0.25 $packets/slot$), node 5 to 8 reserve one slot every five slots (0.2 $packets/slot$), and node 9 to 10 reserve one slot every ten slots (0.1 $packets/slot$). The remaining nodes 11 to 50 do not reserve any bandwidth. The simulation is run for a total of 65,000 slots.

Fig. 9 shows the throughput of each node versus the offered load under $m = 20$ and $\tau = 0$. In this figure, we only show the throughput of nodes 1 to 30. The remaining nodes 31 to 50, have the same result of node 30. Fig. 10 show the results with simulation as two dimensional graph under the same conditions. As shown in these results, the throughput of the guaranteed nodes can smoothly increase up to the reserved bandwidth. On the other hand, the throughput for the UN-guaranteed nodes stabilize at a lower level and every node has almost same result. This means that the guaranteed nodes can access the data channel up to the reserved bandwidth and the other nodes can fairly share the remaining bandwidth.

Figs. 11-12 show the throughput of the guaranteed node 1 and the UN-guaranteed node 15, respectively, for various m (= 10 to 20). The results show that the proposed protocol can guarantee the reserved bandwidth and the guaranteed bandwidth is independent of m. But, the throughput of the UN-guaranteed nodes decreases when m is small. This is because minislots are assigned to the guaranteed nodes. The remaining minislots are used by the UN-guaranteed nodes. Hence, the throughput of UN-guaranteed nodes is worse when m is small.

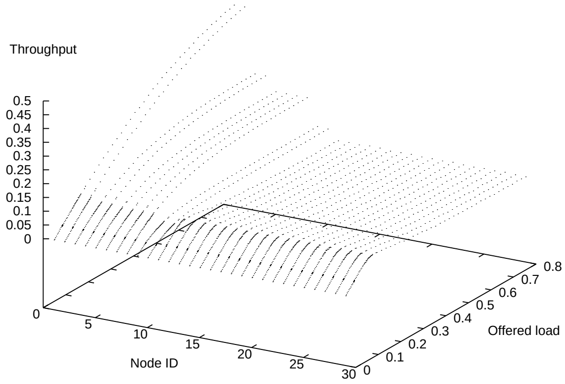

Fig. 9. Throughput of each node.

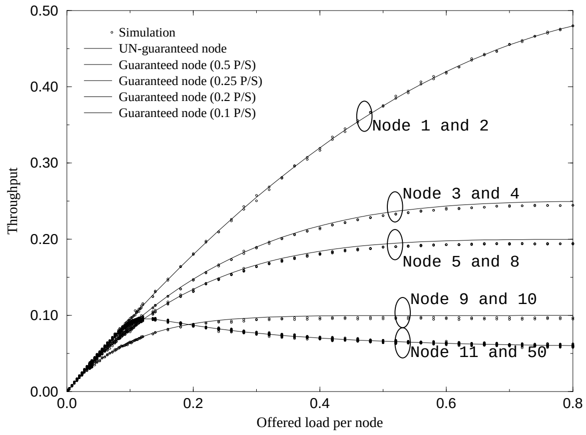

Fig. 10. Analysis result for the throughput of each node.

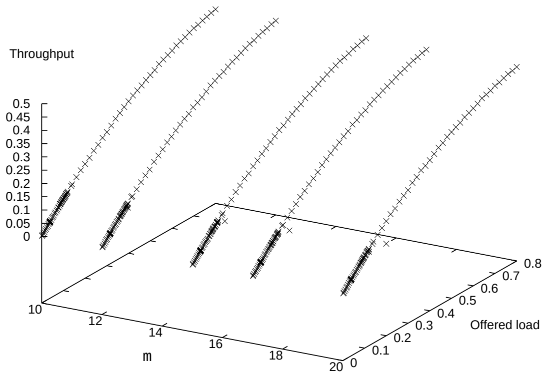

Fig. 11. Throughput of the guaranteed node 1 for various $m = 10$ to 20.

Figs. 13 and 14 show the throughput versus the offered load for guaranteed nodes and UN-guaranteed nodes with

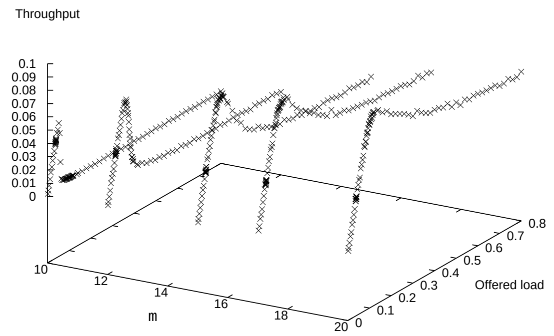

Fig. 12. Throughput of the UN-guaranteed node 15 for various m = 10 to 20.

different τ (=0,2 and 4). In this simulation, we assume that m=20. These figures show that throughput for each node is independent with τ. It means that the proposed protocol can be run regardless of the propagation delay.

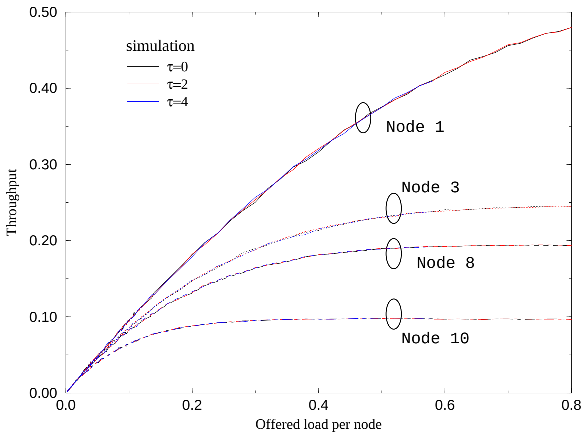

Fig. 13. Throughput of guaranteed nodes for different τ=0, 2, and 4.

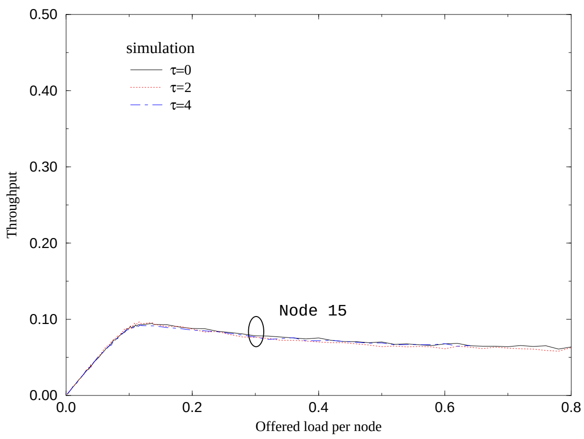

Fig. 14. Throughput of UN-guaranteed node for different τ=0, 2, and 4.

Fig. 15 shows the simulation results of the average delay for each node. For the guaranteed nodes, the delay curve is almost flat. For the UN-guaranteed nodes, the delay at low load region is lower than that of guaranteed nodes. But, the delay rapidly increases at medium and high load regions. The guaranteed node has to wait until a reserved slot is available. On the other hand, UN-guaranteed node can immediately access any minislot when a new packet arrives. However, the minislot may be blocked repeatedly. So, the delay is unbounded. This means that the guaranteed node has some initial delay but it does not increase even when the offered load is high. Moreover, the delay is bounded by the inter-arrival time of the reservation marks. On the other hand, UN-guaranteed nodes have no initial delay is not bounded.

Fig. 16 compares the network throughput with and without reservation capability. The throughput of the proposed protocol is better than the throughput of the contention protocol without reservation capability. With the reservation capability, guaranteed nodes can get up to the reserved bandwidth. Moreover, the remaining bandwidth is fairly shared. So, the throughput can be sustained at higher level even for overload condition. On the other hand, the contention protocol without the reservation capability [10] has a major drawback when the traffic load becomes high.

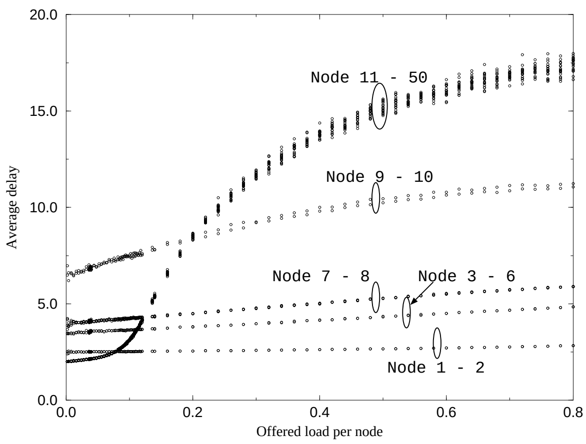

Fig. 15. Delay time of each node.

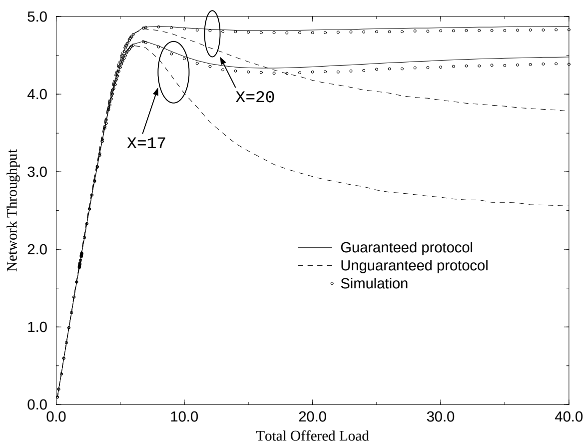

Fig. 16. Network throughput Under m = 17 and m = 20.

IV. Conclusion

In this paper, we proposed a bandwidth guaranteed multi-access protocol for broadcast-and-select WDM local area networks. The proposed algorithm is a contention and reservation scheme, where data channels are dynamically assigned. It is a first approach to add bandwidth guarantee capability on the contention mechanism. The contention-based mechanism can provide high performance for on-demand traffic. Moreover, the bandwidth is fairly shared by all nodes. The reservation mechanism can guarantee the minimum bandwidth for the guaranteed nodes. By reserving minislots instead of the data channel, the proposed protocol utilizes the data channels even when the reservation is not used. This protocol is easily implemented in a distributed environment without the need to maintain any global information. Moreover, the protocol has the same performance for the system with large propagation delays. Although we only describe the protocol for fixed packet sizes, but the protocol can be easily enhanced for the variable-length packet, too [14].

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