8 Tb/s ATM interconnection through optical WDM networks

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ABSTRACT

We propose a novel scheme for interconnection of multiple high-speed (2.5/10 Gb/s) ATM streams through an optical WDM network, with a total network capacity of up to 8 Tb/s. The proposed architecture is based on placing the optical WDM portion of the network in a physically small area, i.e., one central office, or in a single rack. This helps to avoid technological obstacles such as power budget, dispersion, and synchronization limitations, and optical output buffering. The interconnection is an ATM packet switched network, and provides optical contention resolution. We show that the implementation of such a network is possible using currently available optoelectronic technology. Simulation results are presented, indicating network throughput of up to 100%.

Key words: 8 Tb/s ATM interconnection, WDM network, ATM switch, ATM/WDM.

2. INTRODUCTION

Next generation high-speed communications systems will need to support the aggregate bandwidth and low latency interconnection requirements of current and future applications such as supercomputer interconnection, high-quality video conferencing, multimedia distance learning, and real-time medical imaging. Many current approaches favor ATM technology, due to its flexibility and support of multimedia traffic. Currently, 16x16 ATM switches are commercially available, and 256x256 ATM switches are being developed. The output of these ATM switches can be multiplexed to produce an output SONET stream of 2.5 Gb/s.

Here, we propose a novel scheme of interconnecting multiple high-speed (2.5/10 Gb/s) ATM streams with a total network throughput of up to 8 Tb/s. The proposed architecture is shown in Fig. 1; it relies on ATM interconnection through an optical WDM network, and is based on the marriage between the flexibility of ATM technology and the aggregate bandwidth available in all-optical WDM networks. All interconnections between the ATM "islands" or supercomputers through the proposed ATM/WDM network will be transparent to the end-user, therefore capable of forming higher-level size ATM network.

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3. ATM/WDM INTERCONNECTION

3.1 Objectives:

The proposed high-level ATM network meets the following goals: (1) up to 800x800 input/output ports and 2.5 (possibly 10) Gb/s/port interconnection capability, i.e., up to 8 Tb/s throughput; (2) optical packet switching to support ATM packets; (3) optical contention resolution on the transmitter side, implemented by a "reservation" scheme; (4) no optical buffering requirement; (5) easy adaptation to LAN/MAN/WAN (basically distance independent); (6) scalability; and (7) pragmatic implementation using currently demonstrated and available technology, both in the optics and electronics layers.

3.2 General architecture

A general illustration of the ATM/WDM interconnection architecture is presented in Fig. 2. Each node includes one input and one output module. The input module connects the 2.5/10 Gb/s ATM stream (e.g. standard SONET stream) arriving from the ATM island with the optical WDM interconnection where it is optically transmitted and routed through the passive star to the relevant output module. The output module receives the optical data stream from the passive star. The data is then retransmitted via standard ATM stream to the desired ATM island.

To meet the foregoing goals, we place the optical WDM portion of the network in a physically small area, i.e., one central office or in a single rack. All 2.5/10 Gb/s ATM data streams, independent of their distance, are connected (via optical cables, e.g., OC-48) to the central WDM interconnection site. With this approach, the system gains many advantages including: (1) independence of link delay; (2) no optical power-budget limitations; (3) no dispersion limitations; (4) better network management (which can be done electronically over a central electronic bus); and (5) no synchronization problems (all I/O ports will be connected on the same electronic bus, with a single clock). An additional aspect of the proposed scheme is packet-switching on a local-control basis, thus avoiding the huge amount of data processing related to central control approach. Local control can be achieved using carrier-detection technique, and is especially relevant while dealing with network throughput on the order of Tb/s.

4. ATM/WDM INTERCONNECTION NODE DESIGN

A detailed description of the ATM/WDM interconnection node is presented in Fig. 3. Each node contains an input and an output module, a carrier detection module, and a local control unit. All the nodes are optically interconnected through optical fibers and a passive star coupler for the high speed data, and electrically interconnected through a 32 bit electronic bus for central (slow) control.

4.1 Input module:

In the input module, a photodetector detects the 2.5/10 Gb/s SONET stream (or other standard protocol). Then the electrical signal is decapsulated from the SONET frame to standard ATM blocks, and sent into a buffer memory. Management packets are sent to the local control unit electrically. The header of each ATM packet is sent to the local control unit indicating its desired destination, related to a specific output module at the ATM/WDM interconnection site (as illustrated in Fig. 2). The controller then sets the wavelength of the fast tunable laser at the input module to a specific wavelength corresponding to the wavelength of the fixed-tuned optical filter at the adequate output module. From the buffer memory, the ATM packet is transmitted (by modulating the fast tunable laser) through the star coupler to the relevant output module. Prior to the transmission, a small portion of the transmitted light is taped through a coupler to the carrier detector module to resolve contention. The contention resolution scheme is described in the following sections.

4.2 Output module

In the output module a small portion of the received light is taped through a coupler to the carrier detector. The rest of the light is filtered through the fixed-tuned optical filter and detected in a photodetector. The electrical signal, which forms the arriving ATM packet, is then encapsulated into a SONET frame. The control unit also can multiplex management packets into the outgoing stream. Finally, the 2.5/10 Gb/s SONET stream is transmitted via a fixed tuned laser to the remote destination.

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5. CONTENTION RESOLUTION

Each optical receiver (at the output module of each node) is fixed tuned to a specific wavelength. Thus, to prevent contention, it is sufficient to ensure that only one tunable laser (at one of the input modules) will transmit at a specific wavelength, at a given time slot. This is achieved by applying carrier detection technique at the transmitter side, slightly before transmitting the payload data. With this technique, the responsibility of preventing contention is of the transmitter, on a local control basis. This is in oppose to applying a central control technique, which involves a huge amount of processing for queuing and prioritizing procedures, imposing a sever bottleneck of network control.

First, the optical carrier detection technique is described, followed by description of the reservation scheme and the scheduling policies.

5.1 Carrier detection:

The carrier detector module is described in Fig. 4. It is based on coherent heterodyne mixing of light from the transmitter with part of the received light from the star coupler. A small portion of the light at the input module transmitter is used as the local oscillator (LO) of the carrier detector, while a small portion of light from the star coupler at the output module receiver (of the same node) is used as the input signal to the carrier detector. At the carrier detector, both signal and LO are combined through a 3 dB coupler and detected by a photodetector. The photodetector operates as a square-law detector of the electromagnetic fields. The resulting electrical spectrum at the carrier detector after photodetection include the following possibilities: (1) heterodyned signals at different IF frequencies corresponding to the wavelength differences between the LO and other nodes' transmitters; (2) self-homodyne signal between the LO and light from the same transmitter arriving through the star coupler, which will form a strong dc term; and (3) heterodyned signal between the LO and other nodes transmitting to the same receiver (therefore, at the same wavelength). The tunable lasers of the different nodes are designed to transmit with a slight wavelength difference $\delta\lambda$ when transmitting to the same receiver (at the same wavelength). Therefore, the electrical spectrum in case (3) will contain an IF frequency within the range $\delta\lambda$. According to the spectrum possibilities described above, the bandpass filter (located after the photodetector in Fig. 4) is designed to pass only the $\delta\lambda$ IF signal, and to block the self-homodyne dc term, and all the higher order IF signals related to mixings between different wavelengths. The output of the bandpass filter is then digitized and sent to the control unit. A strong signal will appear at the carrier detector output only in case that the LO and at least one additional transmitter are transmitting at the same wavelength (with a slight difference $\delta\lambda$ as designed initially). In that case, the contention resolution unit prevents the transmission of payload data from both modules, and the reservation procedure that follows is described below.

5.2 Reservation:

The reservation scheme is designed to meet the following goals: (1) maximum throughput of 100%, (2) small overhead, < 10%, (3) scalability, and (4) local control. The optical transmission time slots are illustrated in Fig. 5 and 6. As illustrated in Fig. 5, at 2.5 Gb/s transmission bit rate, a 53 byte ATM packet transmission time is approximately 170 ns. An overhead time of less than 10% of that (12 ns) is dedicated for reservation. A four slot reservation scheme is illustrated in Fig. 6. The first slot is dedicated to constant bit rate (CBR) traffics. For this kind of traffics, the reservations are made at the network management level. The network management pre-allocates a fixed number of packet time slots to each CBR traffic proportionally to the requested bit rate during the connection setup. The motivation of pre-allocating packet time slots for CBR in advance is to effectively create TDM-like transmission, which is a very efficient way of transmitting CBR traffics. Since the reservations in this case have been decided beforehand by the network management, during these pre-allocated slots, the corresponding input module always takes the first reservation slot to signal that the packet slot is occupied. All other types of traffics share the remaining slots. Because of the built-in reservation priority, the first input to make a reservation always has the highest priority. As a result, the pre-allocated CBR traffics experience a fix TDM-like delay. To share the remaining reservation slots, the input module selects one of the slots, randomly. Once the input module selects its reservation slot, during that reservation period of 3 ns, the tunable laser at the input module transmits only the optical carrier. The signal is later received in the carrier detection unit, and the carrier detector output signal is sent to the local control unit. In case of no carrier detection, the laser continues to transmit the optical carrier during the rest of the reservation time slots, so it can be detected by other potential nodes transmitting in the following reservation slots. In case of a carrier detection, it means that

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an additional node transmits at the same wavelength. Therefore, to avoid contention, the packet transmission is delayed until the next transmission time slot, i.e., delayed by about 185 ns.

For the proposed system, the input module does not retry another reservation upon reservation failure before the last reservation slot. However, for the system with separated reservation channel and parallel data channel, retrying leads to much better performance. Optical transmission time slots for a system with parallel payload and reservation channels are illustrated in Fig. 7.

5.2.1 Scheduling

The buffer memory in the input module consists of many FIFO queues corresponding to the destination output modules. Shown in Fig. 8, upon arrival at the buffer memory a packet is sorted into the corresponding queue according to its destination output module. It waits in the queue until the scheduler and reserver succeed to secure permission to transmit.

Although reservation eliminates output contention, – because the transmitter transmits one packet at the time – each input module still has to resolve the contention to transmit among its non-empty queues. In doing so, each input module schedules the transmission by selecting one non-empty queue accordingly to the scheduling policy. The first packet of the selected queue will then be transmitted upon successful reservation. In general, a scheduling policy should be efficient and fair. In this section, we present two scheduling algorithms: random and SLIP. Even though the random policy performs worse than the SLIP policy, it gives us better idea on the impact of the number of the reservation slots on the maximum throughput. We now present the random policy along with the analysis and simulation results. Afterwards, we present the SLIP and its results.

5.2.2 Random policy

Under the random scheduling policy, each input module chooses a queue uniformly from its non-empty queues. This random selection prevents queues from not being serviced, i.e., starving. Although it is very simple to analyze and simulate, the random policy is not as simple as the SLIP to implement. Furthermore, its performance is inferior to that of the SLIP. However, as mentioned before, the analysis of the random policy is a good indication of the effectiveness of the reservation policy. Following is the performance analysis of NxN system with M reservation slots.

For NxN system with M reservation slots under a uniform identically independent (i.i.d) traffic, the analysis begins with the assumptions that the buffer size is infinite and all queues are heavily loaded. Under these conditions the maximum throughput is equal to the probability of a packet destined for an output in a given time slot.

$$\text{Max. throughput} = \Pr\{\text{a packet destined for output j}\} \tag{1}$$

Considering our reservation policy, the output only has a packet destined to it when at least one successful reservation occurs in any of M slots. Therefore,

$$\text{Max. throughput} = \Pr\{\text{ at least one successful reservation}\} \tag{2}$$

Because of the uniform selection of the scheduling and reservation policies, the probability that input module i makes a reservation to output j in slot k is:

$$\Pr\{\text{input i makes a reservation to output j in slot k}\} = \frac{1}{NM} \tag{3}$$

The reservation succeeds only when there is one reservation in a given slot. Hence, the probability of a successful reservation in any given slot is:

$$\Pr\{\text{a successful reservation in slot k}\} = \frac{1}{M}\left(1-\frac{1}{NM}\right)^{N-1} \tag{4}$$

Therefore, for all reservation slots,

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$$\Pr\{\text{ at least one successful reservation}\} = 1\,1 - \left(1 - \frac{1}{M}\left(1 - \frac{1}{NM}\right)^{N-1}\right)^{M} \quad (5)$$

As previously defined, the maximum throughput is:

$$\text{Max. throughput} = 1\,1 - \left(1 - \frac{1}{M}\left(1 - \frac{1}{NM}\right)^{N-1}\right)^{M} \quad (6)$$

The above equation clearly shows that, for a system with large N and M, the maximum throughput asymptotically approaches 63%. Table 1 shows the comparison of the analytical and simulation results.

M	Analytical	Simulation
10000	0.6321	--
64	0.6296	--
16	0.6216	--
7	0.6069	0.60-0.61
4	0.5851	0.57-0.58
2	0.5247	0.52-0.53
1	0.3798	--

Table 1. Shows the maximum throughput comparison of the analytical and simulation results for different number of reservation slots, M. The results are for 16x16 system with a uniform i.i.d traffic.

Fig. 9 shows the comparison of the simulation result of the random policy with different number of reservation slots with the well-known FIFO result for 16x16 switch. In summary based on our analysis and simulation results, four reservation slots seems to be a good tradeoff between performance and overhead.

5.2.3 SLIP policy

Unlike the random policy, SLIP policy selects a non-empty queue based on the queue priority. Similar to the least recently used (LRU) policy, a queue which is chosen in the present time slot will be given the lowest priority in the next time slot. As shown in Fig. 10, the priorities of the queues are ranked in the decreasing order relative to the position of the priority pointer. In this figure, the scheduler selected the first queue in the previous time slot. Based on the SLIP policy, the priority pointer now points to the second queue. Consequently, the first queue now has the least priority and the second queue where the pointer is has the highest priority. Because of the build-in priority mechanism, input module always allocates transmission time to all of its queues fairly. More importantly, under a heavy load, the policy adapts to TDM-like transmission allocation which results in the maximum throughput of 100%.

In addition to its superior performance, the SLIP policy is much simpler to implement in hardware than the random or other scheduling policies. The priority pointer can be implemented inexpensively using a priority encoder. Fig. 11 shows the SLIP performance in comparison with a FIFO input-queued network and an output-queued network. Although it doesn't perform as well as an output-queued network in term of the average delay, in contrast with an output-queued network, the SLIP provides realistic solution to actual building of such a high throughput switch.

6. OPTOELECTRONICS TECHNOLOGY: REQUIREMENTS AND CURRENT STATUS

To implement the proposed ATM/WDM interconnection network, its design must be based on components and devices that are either available or in advanced stage of development. Since the interconnection of the aggregate bit rates are

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designed to be implemented optically, the success in implementation is derived from the limitations imposed by the state of the art of optical and optoelectronic components and devices. It should be pointed out that a grate deal of flexibility is achieved due to the proposed interconnection design, being physically in a small geographical location (one office or a single rack). This allows very modest requirements of power budget, dispersion, and propagation-based latency. The coherence requirements for the carrier detection scheme can also be satisfied relatively easily due to the short propagation lengths involved. For example, polarization problems can be solved by the use of polarization maintaining (PM) fibers.

However, there are three key parameters that are crucial and impose limitations on the network capacity: (1) laser tuning range, (2) optical wavelength selectivity, i.e., filter finess, and (3) tuning setup time of the tunable lasers. The two first parameters derive the channel spacing and total number of channels in the WDM portion of the network, while the third parameter derives the maximum bit rate of which the network can operate on a packet switched basis.

6.1 Laser tuning range:

The proposed network is designed to interconnect 100x100 (optionally 800x800) ATM streams running at 2.5 (possibly 10) Gb/s each. The largest continuous tuning range demonstrated in a semiconductor laser is of 7 nm [1],[2]. There are DBR lasers with a "quasicontinuous tuning range (involving mode hopes) of 11 nm [3]. In addition, there are integrated arrays of tunable lasers with non-overlapping tuning range, that have already been demonstrated with a quasicontinuous tuning range of over 20 nm [4]. A new technology involving tunable lasers arrays is the vertical cavity surface emitting lasers (VCSELs) that are in an advanced stage of development [5]. With the use of VCSELs at the transmitters of each input module, the interconnection WDM subnetwork capacity can be extended N times larger, as illustrated in Fig. 7. Each element in the laser arrays of all the nodes are optically connected through a different passive star, forming N different optical subnetworks. In the receiver side, there are filter arrays where each element in the arrays of all nodes are connected to the corresponding one of N subnetwork through the corresponding passive star. With this architecture, the capacity of the WDM portion of the interconnection network is significantly extended by overcoming the tuning range limitation. In Fig. 7, a 3x3 laser array interconnection architecture is illustrated. There are 9 independent optical subnetwork, including 8 for payload data, and one for optional network control issues. This network can possibly interconnect 100x8 nodes supporting possibly 10 Gb/s ATM streams each, i.e., an overall capacity of 8 Tb/s.

6.2 Wavelength selective filters

Assuming a 100x100 ATM interconnection network, and an available tuning range of 10 nm, the required channel spacing in the optical WDM network is of 0.1 nm, or 12.5 GHz. Assuming a frequency spacing of twice the bit rate to avoid crosstalk between the channels, this configuration (of 100x100 channels, and 10 nm of tuning range) can support ATM streams of more than 5 Gb/s. There are many demonstrations of filters that can perform wavelength selectivity of such spacing, with finess grater than 200, including Fabry-Perot [6]-[8] and Mach-Zender [9] filters. It should be noted that the required filters in the network are fixed tuned and not tunable, which makes it even easier to implement.

6.3 Laser tuning speed

In the case of standard 53 byte ATM packets arriving at 2.5 Gb/s bit rate, the optical transmission duration of each packet is approximately 170 ns, plus 15 ns overhead for reservation, as illustrated in Fig. 5. Accordingly, in case of employing two tunable lasers per optical transmitter at the input module (Fig. 4), the tuning setup time must be shorter than about 150 ns. While transmitting a packet by one laser, the header of the next packet is read and sent to the local control unit, so it can control the second tunable laser simultaneously and set its wavelength according to the destination of the second packet. Current technology offers both DBR and DFB lasers with tuning speed significantly faster than the 150 ns requirement. For example, there are 3 section DBR lasers that have been demonstrated with tuning speed in the range of 8-20 ns [10]. There have also been demonstrated tuning speeds in the order of a few ns of commercial DBR lasers of GEC-Marconi. By using such fast lasers, one laser per transmitter is sufficient in the input module, and the setup time will add a few ns of overhead to the overall time slot of 185 ns.

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7. CONCLUSIONS

We have presented a novel scheme for interconnection of multiple high-speed (2.5/10 Gb/s) ATM streams through an optical WDM network, with a total network capacity of up to 8 Tb/s. The proposed scheme leads to many technological advantages. The basic concept of placing the optical WDM portion of the network in a very small geographical area, i.e., a single rack, gains many advantages: power budget limitation is minimized , dispersion effects are negligible, and synchronization is provided via a central electronic bus. The proposed interconnection network is packet switched, and provides optical contention resolution. It was shown that the implementation of such interconnection is very realistic, based on current available technology. Simulation results indicate high efficiency of the network, with a throughput of 100%.

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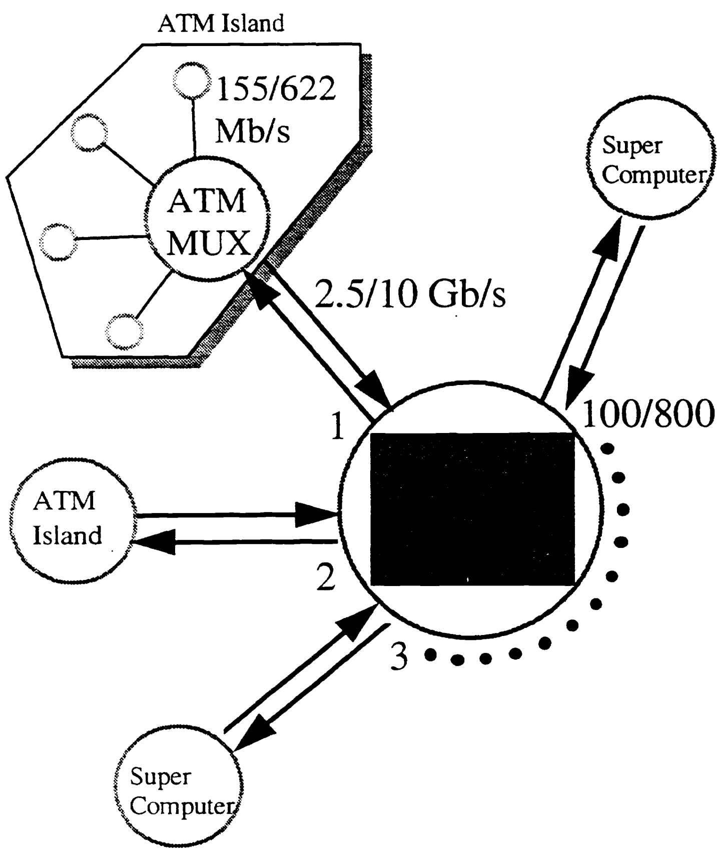

Fig. 1. High-speed (2.5/10 Gb/s) ATM interconnection streams

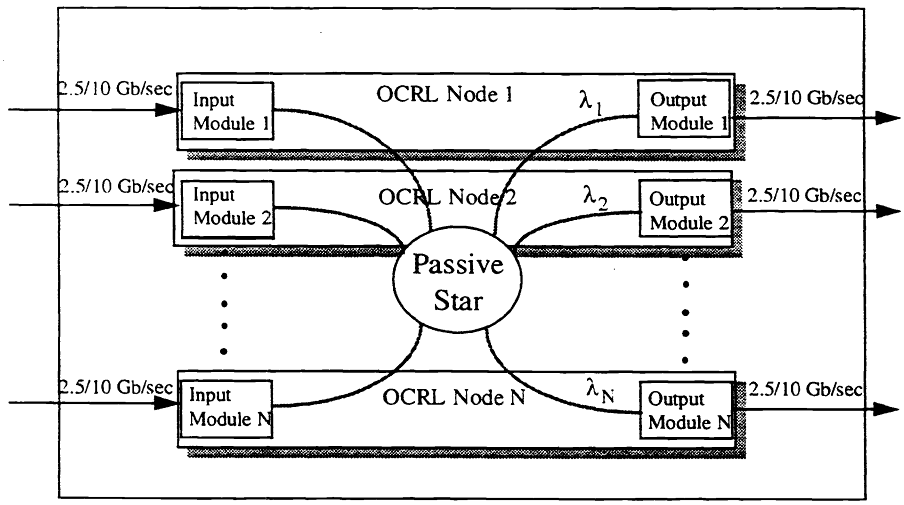

Fig. 2. Proposed interconnection multi Tb/s ATM/WDM site (a single rack)

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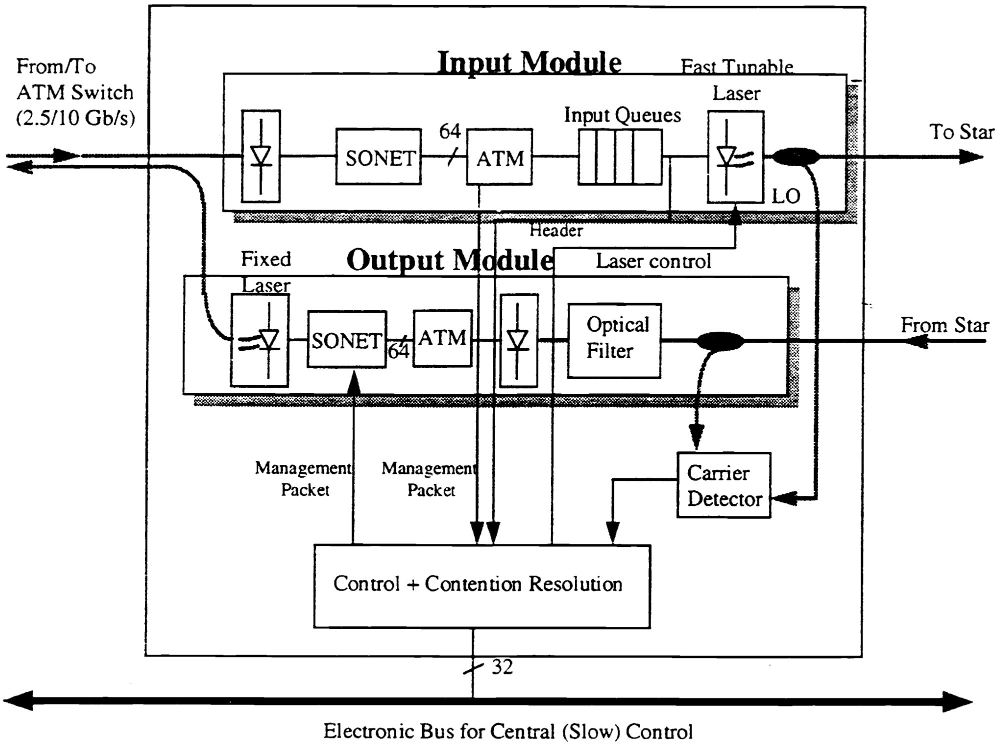

Fig. 3. Proposed interconnection node: Input + Output Modules

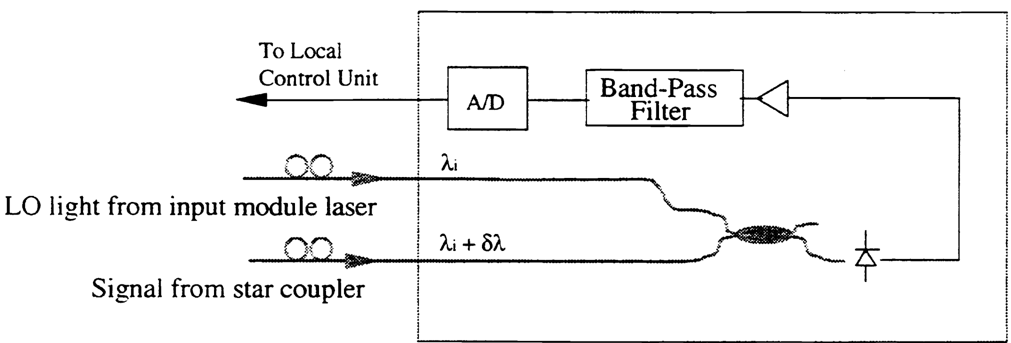

Fig. 4. Carrier Detector

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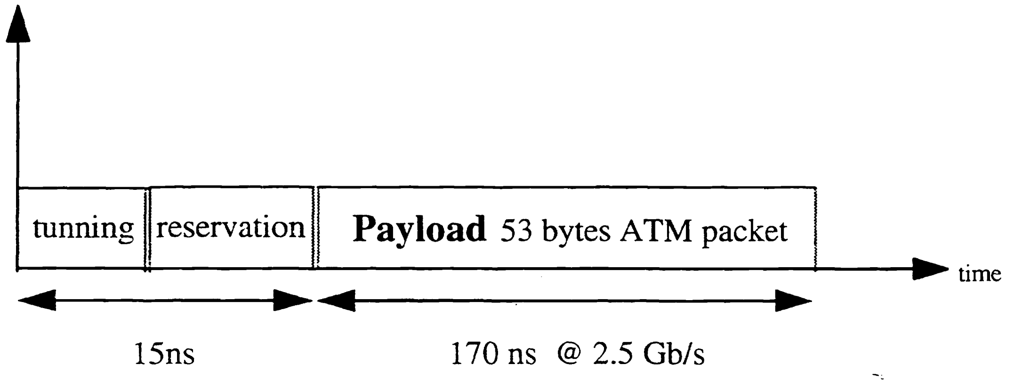

Fig. 5. Optical transmission time slots

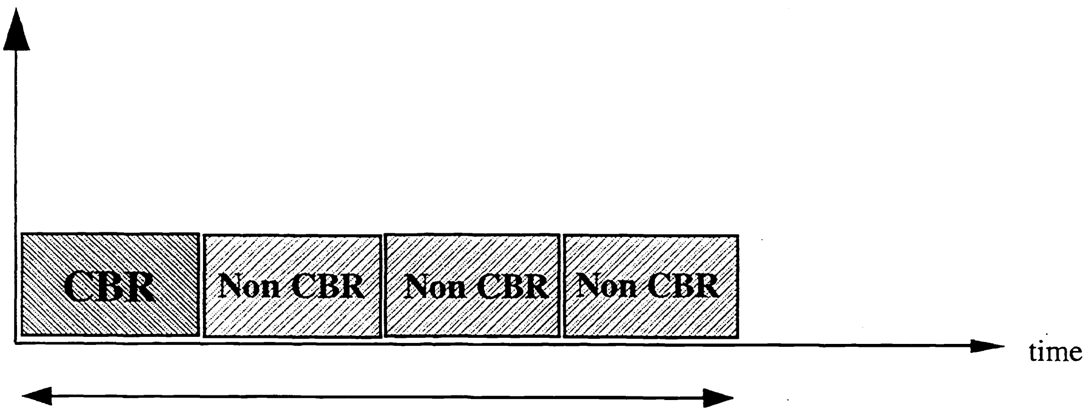

Fig. 6. Four reservation slots

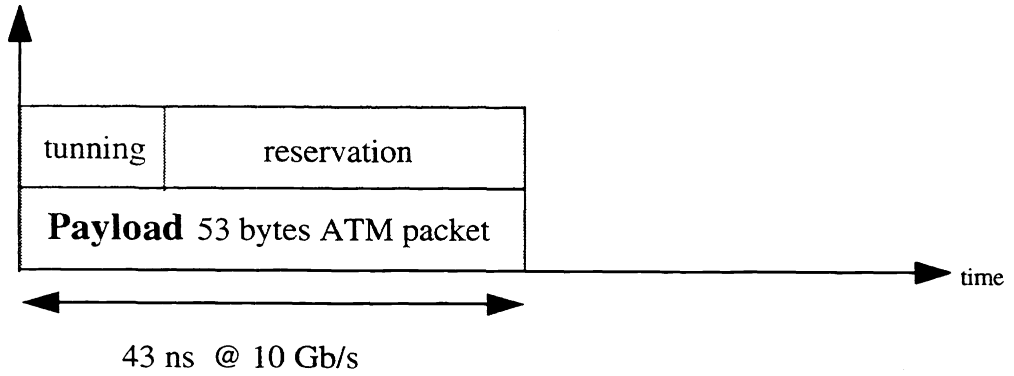

Fig. 7. Optical transmission time slots for a system with parallel payload and reservation channels.

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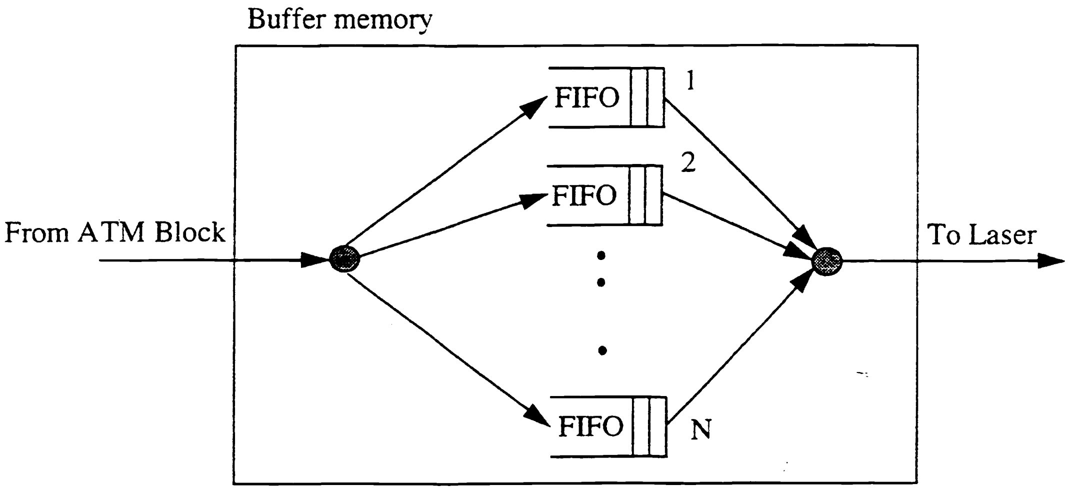

Fig. 8. Buffer memory organization.

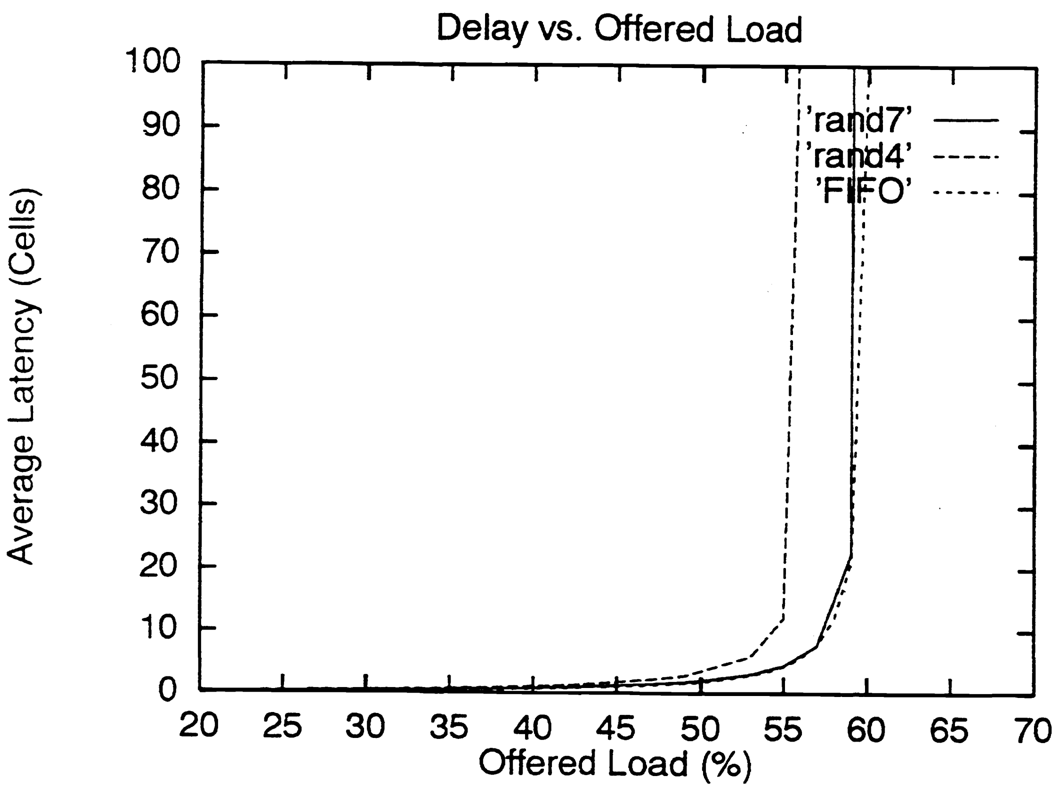

Fig. 9. Performance of the random policy with different numbers of reservation slot compared with the FIFO policy.

Results obtained using simulation for 16x16 system under a uniform i.i.d traffic.

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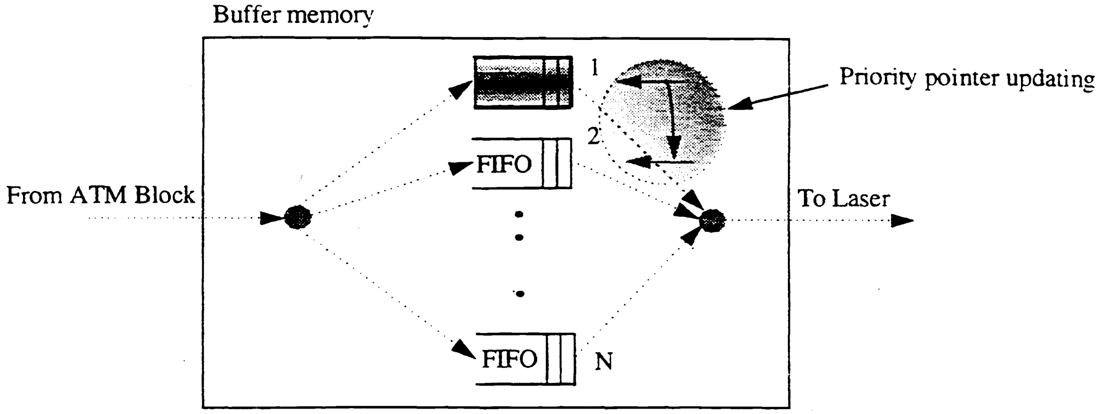

Fig. 10. Priority pointer updating under the SLIP policy.

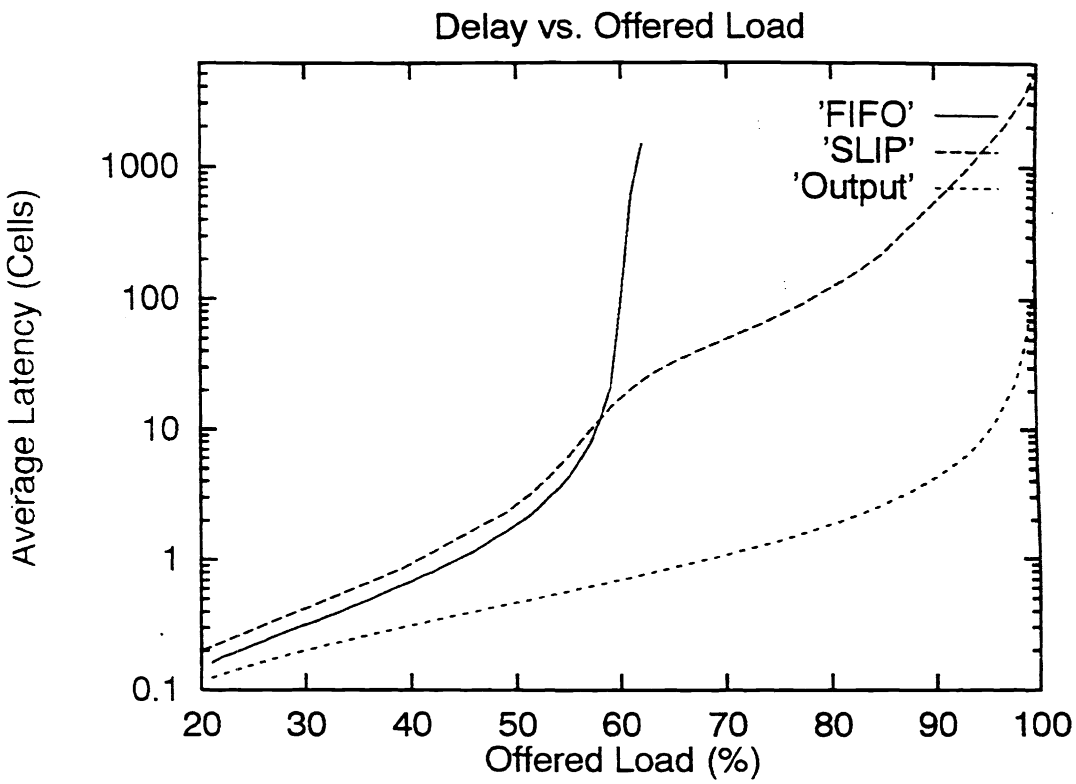

Fig. 11. Performance of the SLIP policy compared with the FIFO policy and an output-queued. Results obtained using simulation for 16x16 system under a uniform i.i.d traffic.

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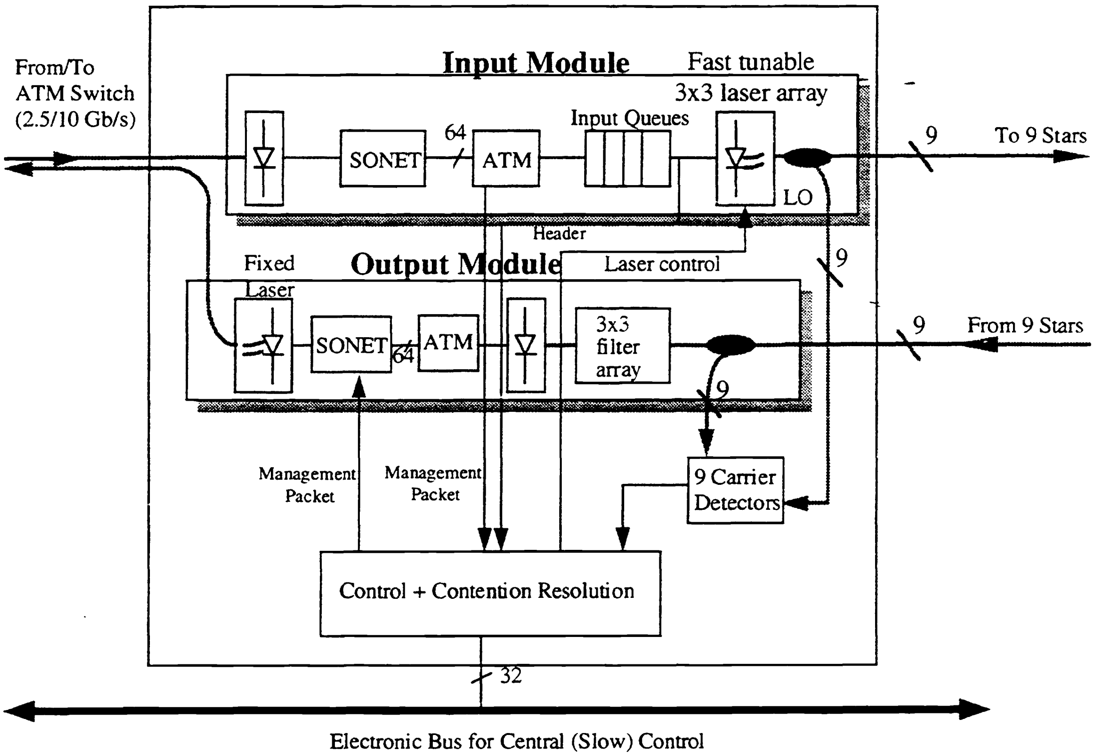

Fig.12. Proposed interconnection node utilizing a 3x3 optical subnetworks scheme

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