Node Architecture and Protocol of a Packet-Switched Dense WDMA Metropolitan Area Network

Chun-Kit Chan, *Member, IEEE,* Frank Tong, *Senior Member, IEEE,* Lian-Kuan Chen, *Member, IEEE,* Kwok-Wai Cheung, *Senior Member, IEEE, Member, OSA,* and Eddie T. P. Kong

***Abstract*— This paper proposes a new node architecture and protocol for a wavelength division multiple access (WDMA) packet-switched metropolitan area network. The network operates on a dual-bus topology and the tunable-transmitter and fixed-receiver scheme is adopted to facilitate data multiaccess. The network protocol runs on a cycle mechanism and the cycle length can be adaptively changed according to the data traffic, thus provides high throughput. The photonic implementation of the proposed network architecture and network nodes are discussed and a new packet-signaling scheme is proposed to avoid data collision during multiaccess. An experimental demonstration is also presented to show its feasibility.**

***Index Terms*— Optical network, packet-switching, protocols, wavelength division multiplexing (WDM).**

I. Introduction

THE ever-increasing demand in communication bandwidth cannot be met with the existing infrastructure that largely based on copper and optical fiber carrying a single wavelength. To support future bandwidth-hungry Internet services where multiple interactive digital video- and voice-data and other large data files are required to be delivered over long distances, wavelength division multiple access (WDMA) is probably the most powerful technique to unlock the enormous bandwidth in optical fiber. Previous approaches to realize WDMA networks were largely confined to a star-based topology [1], [2] using a fixed-tuned transmitter and tunable receiver (FTTR) scheme, where the optical receiver at each node will receive one to all wavelength channels from the transmitting nodes. A 32-channel WDMA prototype network using DFB laser transmitters with different wavelengths was reported by the IBM researchers in [3], [4]. Each channel had a capacity of 1-Gb/s, with the channel spacing set at 100-GHz. A dense WDMA star network with 100 channels, each spaced by 10-GHz and at a bit-rate of 622-Mb/s, was also reported by the NTT researchers in [5]. However, the channel selection for the NTT group was based on thermal tuning in a Mach–Zehnder lattice filter, and on piezoelectric tuning of a scanning fiber Fabry–Perot filter. The tuning time was largely limited to ms range, rendering the network unsuitable for packet switching.

This paper intends to describe our work on a packet-switched metropolitan-area photonic network based on a dual looped-back bus configuration. The network is operated in tunable transmitter and fixed-tuned receiver scheme (TTFR) with a centralized multiwavelength light source. Each wavelength channel is partitioned into different time slots; and a simple and efficient media access control (MAC) protocol, called adaptive-cycle tunable access (ACTA) protocol [6], is employed to improve the channel utilization and the fairness among all network nodes. The protocol works in a cycle mechanism and the cycle-length can be adaptively adjusted according to the traffic requirement in the network. Simulation results show that high throughput and good fairness can be achieved. The occupancy of each wavelength channel is signified simply by means of an radio frequency (RF) pilot tone, being multiplexed with the transmitting data, thus assuring that no data collision will occur during data multiaccess. The channel sensing time is of nanosecond or submicrosecond range, thus packet switching of gigabits per second data is allowed.

The paper is organized as follows. Section II outlines the network architecture, and the details and the performance of the media access protocol, ACTA will be described. Section III presents the photonic implementation of the head-node and the network nodes. The packet-access signaling scheme will also be illustrated. Section IV discusses the bit error rate (BER) analysis of the wavelength channels as the network capacity is mainly limited by the accumulation of amplifier noises along the network. Some experimental results will be given in Section V and our work will be summarized in Section VI.

II. Tunable Channel Packet-Switched WDMA Dual Bus Network

A. Network Architecture

The proposed network architecture is shown in Fig. 1, consisting of one head node and many network nodes, arranged in a dual counterpropagating looped-back bus configuration. Each network node may serve as a router to local loop connecting to hundreds of workstations. The number of network nodes is scalable, mainly limited by the optical amplifier noise, and to a lesser degree, by the optical modulation index of the data channels, as will be discussed in Section IV. In addition to high efficiency and throughput, the dual looped-back bus

Manuscript received January 13, 1999; revised August 12, 1999. This work was supported in part by Hong Kong Research Grant Council CERG CUHK4157/98E and CUHK 4170/97E.

C.-K. Chan was with the Optoelectronics Research Centre, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong. He is now with Bell-Laboratories, Lucent Technologies, Holmdel, NJ 07733 USA (e-mail: cckchan@lucent.com).

F. Tong, L.-K. Chen, K.-W. Cheung, and E. T. P. Kong are with the Lightwave Communications Laboratory, Department of Information Engineering, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong.

Publisher Item Identifier S 0733-8724(99)08934-3.

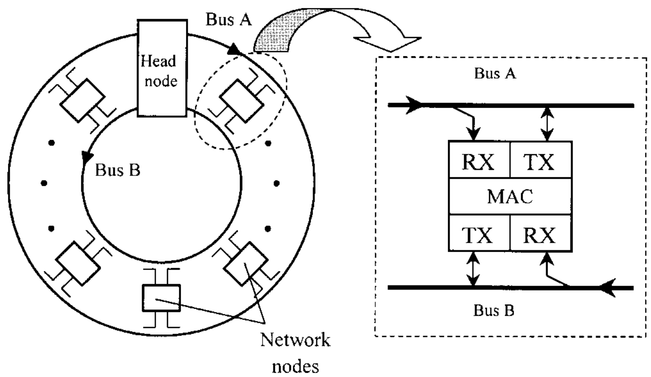


Fig. 1. Dual ring/bus network architecture. Inset shows the basic configuration of a network node. RX: receiver, TX: transmitter, and MAC: media access control.

configuration can also enhance the network's survivability in case of node failure or fiber break. The network node next to the failed node or fiber will route all traffic from one ring back to the other, which is similar to the self-healing feature [7] in the SONET ring network. Thus, the proposed network is compatible with the existing deployed SONET ring networks. Besides, the head node also serves as the fault manager to which all other network nodes report their surveillance and status information. In this way, the head node will be notified in case of failure in any network component, such as partial failure of optical amplifier attaching to each node, and thus appropriate remedies can be made promptly.

At the head node, there is a centralized light source which emits multiple and equally spaced wavelengths simultaneously on each bus and they are shared among all network nodes to perform data communications within the network. Thus, no laser source is required at each network node. This centralized light source design [8] has the advantage of ease of control and maintenance as all light sources can be monitored simultaneously at one site. Nominally, channel separation is largely capped by the neighboring channel crosstalk due to drifting of emission wavelength caused by thermal or device aging. Centralized light source allows close monitoring of emission wavelengths and power, thus making dense WDM (channel spacing $<$50 GHz) network of $>$100 channels over $\sim$30 nm Erbium gain bandwidth possible. Note that the optical outputs from these sources are continuous wave without any data encoding. The data will be encoded on the destined wavelength channel at the transmitting network node via an optical modulator, possibly up to about 60 Gb/s with the present technology.

For all-optical networks, multiple access can be achieved either by TTFR or FTTR. For the TTFR case, each node is assigned with a fixed wavelength for data reception. The receivers at node i will only listen to wavelength channel i (λ_i). Nodes intending to send data to node i have to tune their transmitters to wavelength λ_i. For the FTTR case, each node is assigned with a specific wavelength for data transmission. To transmit data from node j to node i, signaling messages have to be first sent to inform node i to tune its receiver to wavelength λ_j for data reception. However, in FTTR, there exists the problem of receiver contention when data from more than one transmitting node may arrive at the same destined node at the same time. A possible solution to such problem is to use switched delay lines [9]. In our network, we adopt the TTFR scheme to eliminate the receiver contention problem and we also employ a new and simple packet access-signaling scheme (Section II) to avoid data collision during transmission.

Because of the dual bus configuration, each network node is equipped with two sets of transceivers, one for each counterpropagating bus, as shown in Fig. 1. In normal operation, Bus A and Bus B operate independently. Wavelength channels that are launched by the head node will terminate at the end-of-bus node or head node after one complete circulation. In order to support the multiple access using TTFR approach, each transceiver consists of a wavelength-tunable transmitter and a fixed-wavelength receiver, as shown in Fig. 2. The transmitter may consists of a tunable add–drop multiplexer (ADM), such as acousto-optic tunable filter based ADM [10] or arrayed-waveguide-grating-based (AWG) ADM [11], to select the destined wavelength channel from the incoming multiple wavelength channels from the head node, and encode the local data onto it via an optical modulator. The detection of channel availability (packet access control) and selection of wavelength channel are controlled by a MAC unit (Section II-B). The unselected wavelength channels will be passed onto the next node. On the receiver side, it may consist of an optical demultiplexer, such as AWG or a demultiplexer based on a fiber Bragg grating [12], to select a particular wavelength assigned to that node for data reception.

In this network design, the number of network nodes can be greater than the number of available wavelengths by sharing the same wavelength channel with more than one network node in a round-robin manner, thus enhancing the network scalability. Considering that there are N wavelength channels, say $\lambda_1, \ldots, \lambda_N$, generated at the head node, the first node to the Nth node will be receiving at $\lambda_1 \ldots$ to λ_N, respectively. Then, the wavelength assignment will be repeated as illustrated in Fig. 3, though not necessarily in exact sequence. For example, the $(N+1)$th node, the $(2N+1)$th node and so on, will also be receiving at λ_1 while the $2N$th node, the $3N$th node and so on, will be receiving at λ_N. With this arrangement, the exact destination of each data packet carried on a certain shared wavelength channel can be further determined by examining the destination address contained in the packet header upon detection at the respective receiving network nodes.

B. Medium Access Control Protocol

We propose to deploy ACTA protocol as the MAC protocol to control data transmission. Basically ACTA is a very versatile protocol and follows a cycle mechanism with slotted access. The cycle length, which corresponds to the number of time slots in a cycle, can be adjusted according to the traffic load of individual nodes so as to enhance the network utilization and ensure fairness for all network nodes.

The protocol works as follows. The head node generates cycles, each of which contains a sequence of fixed-sized unoccupied time slots in all wavelength channels in both

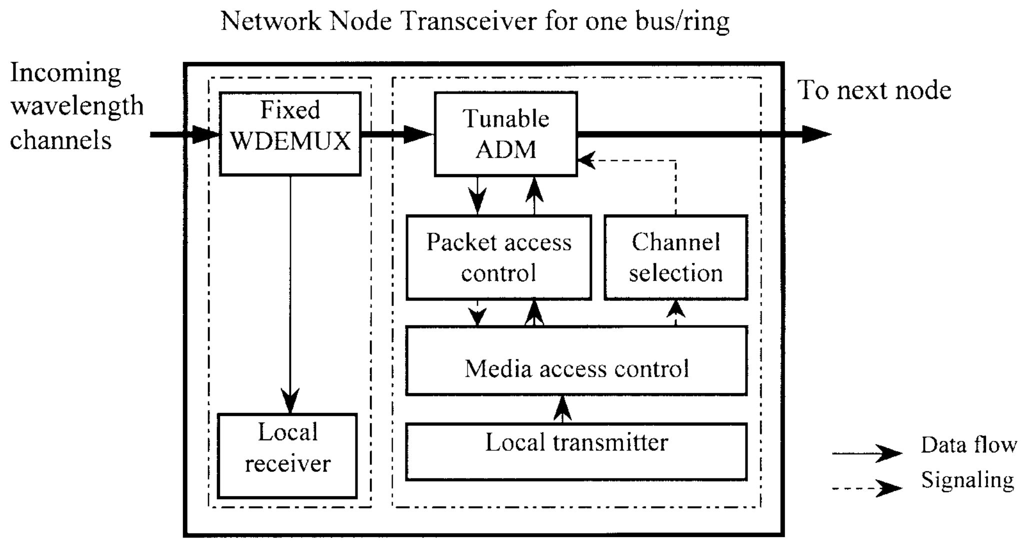


Fig. 2. Architecture of a network node transceiver. WDEMUX: wavelength demultiplexer and ADM: wavelength add–drop multiplexer.

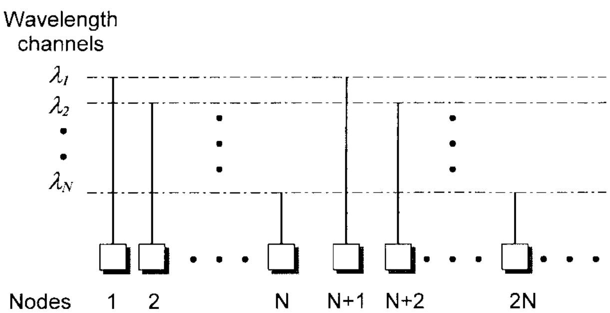


Fig. 3. Round-robin wavelength channel assignment for the receiving nodes. Each node can only receive data from one designated wavelength channel. The transmitters are not shown.

clockwise and counterclockwise directions. Each network node can access the time slots and transmit their data on each bus. However, each node has a transmission quota that one can only occupy at a maximum of N_q time slots in each cycle. Initially, the cycle length, C, is set at the sum of the maximum allowable load from each of all M network nodes. That is, $C = C_{\max} = MN_q$. It will be adaptively changed according to the traffic condition to improve the network throughput. There are two control-status flags issued. The *Cycle-Start* flag is issued by the head node in the first time-slot of each generated cycle to indicate the beginning of the cycle, while the *Slot-Occupied* flag is issued in every time slot by each individual network node to indicate the occupancy of that time slot.

We distinguish the ACTA's operation into receiving and transmitting mode. In receiving mode, the network node will only demultiplex and tap the assigned receiving wavelength channel for data reception. In data transmission, the media access procedure consists of two sequential phases: (1) channel tuning, and (2) channel access. Fig. 4 shows the state diagram of the ACTA protocol. In the channel-tuning phase, the transmitter module will select the correct wavelength channel for the destination node. The availability of the time slot will be checked. If the *Cycle-Start* flag is detected and an unoccupied time slot is found to be available in that cycle, the channel access phase will then permit the data to be encoded on the select wavelength channel, and set the *Slot-Occupied* flag. The transmitting node will stop writing its data for one of the following conditions. First, the transmitting node has used up all its quota of N_q time slots allowed in the current cycle. Second, the outgoing packet is set for a wavelength different than the selected wavelength. Finally, if there are no more time slots available in the current cycle, the transmitting node must wait for the next cycle.

After one complete cycle, the cycle utilization is computed at the end-of-bus node or the head node. The results are then used to calculate the duration for the next cycle in accordance to the utilization of the current cycle using an adaptive algorithm given by

$$\text{New Cycle Length} = \frac{\text{Current Cycle Length} \times \text{Cycle Utilization}}{\text{Controlled Load } L_c}$$

where the cycle utilization is the number of time slots used in the cycle divided by the current cycle length, and controlled load L_c is a parameter specifying the desired throughput under heavily overloaded condition. Set by the head node, L_c basically determines how far the new cycle length can be expanded or contracted. L_c is typically set below unity in order to preserve its adaptability for cycle expansion. Each cycle length is bounded by a maximum value of $C_{\max}$, though the new computed cycle length may be larger than $C_{\max}$.

The adaptive cycle feature is particularly designed to resolve the fairness and efficiency issues. Suppose some of the network nodes have their quota filled up while others have very few data packets to send, the calculated new cycle length will be reduced accordingly after the initial cycle. In this way, those transmitting nodes have few packets to send need not wait for a long cycle time, thus improving the overall efficiency.

Simulations are performed to demonstrate the efficiency and effectiveness of ACTA protocol on a 64-node network with eight wavelength channels, with each channel operating at 100-Mbps [13]. The packet size is 512 bytes. We assume

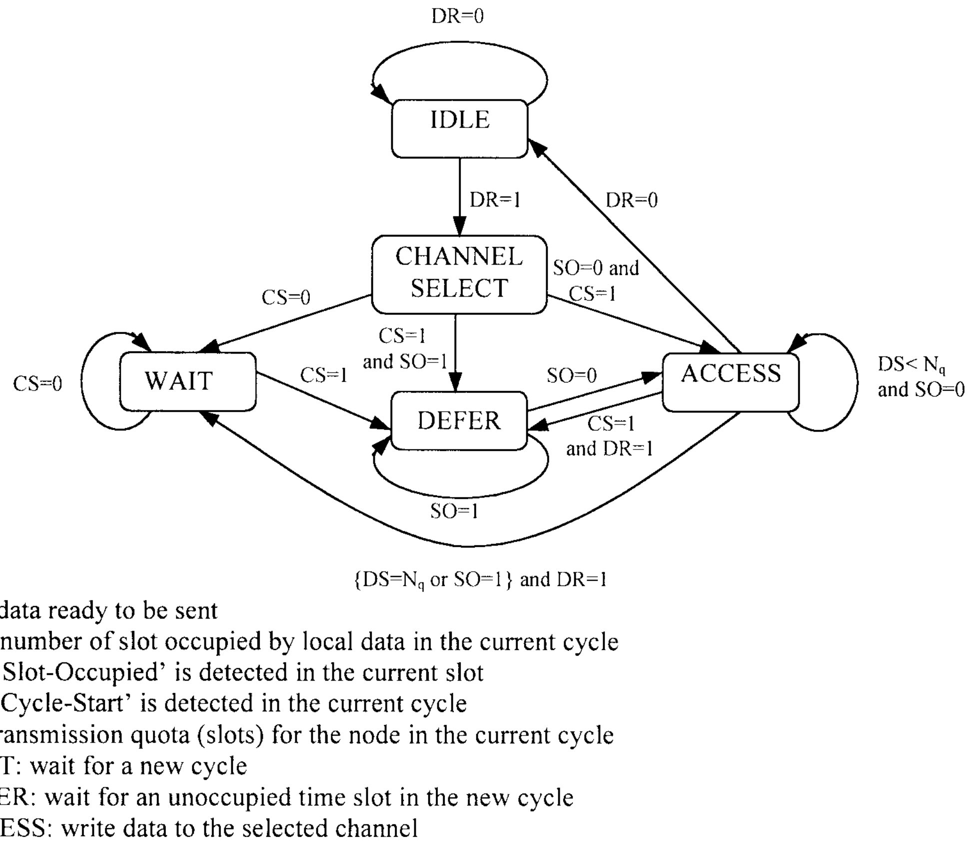


Fig. 4. State diagram for ACTA protocol in data transmission mode.

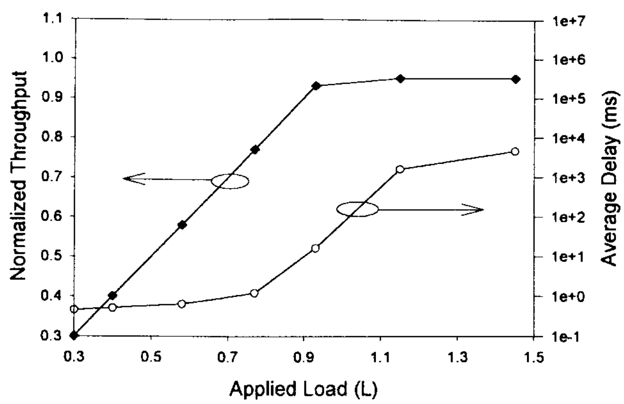


Fig. 5. Simulation results: normalized throughput and average delay of ACTA protocol under different applied load (controlled load $L_c = 0.95$).

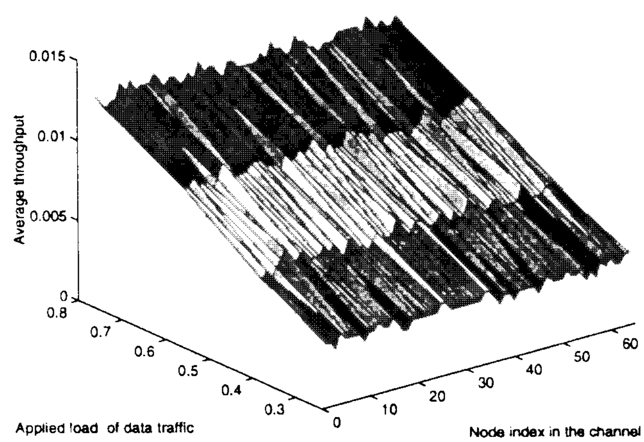


Fig. 6. Simulation results: fairness of the ACTA protocol over 64 nodes under different applied load (controlled load $L_c = 0.95$).

the network nodes are spaced equally apart, and the traffic is distributed uniformly among all nodes with L_c equals to 0.95. The round-robin wavelength assignment of the receiving nodes as shown in Fig. 3 is used. Fig. 5 plots the efficiency with respect to the traffic load, showing that the normalized throughput is close to unity at an applied load of 0.9. Fig. 6 depicts the fairness plot as a function of applied load over 64 nodes, showing that the fairness can be maintained fairly well even under heavily loaded condition.

There are several advantages of ACTA over other protocols. First of all, ACTA is very simple and lightweight. Unlike DQDB [14] no request registration is required. Each slot only needs two control status flags, *Cycle-Start* and *Slot-Occupied*, and can be made slot-compatible to many other standard protocols such as ATM or DQDB. Consecutive slots going to the same destination can be transmitted together, thus the reassembly of large packets is simplified. Second, the performance is independent of the round trip time. The normalized throughput can approach unity and the fairness can be maintained fairly well even under heavily overloaded conditions. Network utilization is high even when only a single node is transmitting. Third, it is adaptive to different traffic. Since ACTA is based on an adaptive cycle mechanism, it can adapt itself to different traffic conditions. In particular, it behaves well under nonuniform traffic conditions and does

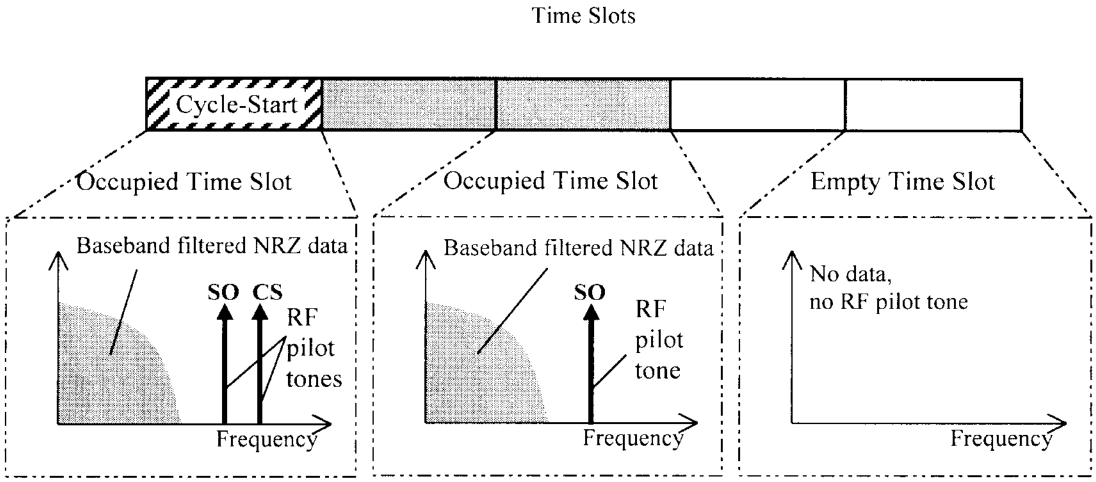


Fig. 7. Packet access signaling.

not have pathological problems such as lock out in 2-node competition situations that affect many other protocols.

III. Photonic Implementation of a Network Node

The proposed dual bus network can be realized with the existing photonic and electronic technologies. The choice of components and subsystems depend on many factors including relative maturity, robustness, tolerances, performances, cost, etc. In the following subsections, we will describe our new packet-access-signaling scheme to avoid data collision during channel multiaccess and the photonic techniques to realize the head node and the network nodes.

A. Packet-Access Scheme

Packet-access signaling techniques are required to coordinate and avoid collision during data transmission among all nodes. To facilitate the access of the time slots on each wavelength channel, baseband data packets are added with an RF pilot tone as an occupancy indicator or the *Slot-Occupied* flag for that time slot (see Fig. 7). For simplicity, all channels share the same tone for the *Slot-Occupied* flag. We also add another RF tone of different frequency to the first time slot in each cycle as a *Cycle-Start* flag to indicate the start of a cycle, as required by the ACTA protocol. Data packets can only be transmitted in a time slot that the *Slot-Occupied* flag is detected, and the output data packets will then be embedded in the wavelength channel together with a new *Slot-Occupied* flag. In this way, collision-free transmission of out-going data packets on any wavelength channel can be assured. The pilot tone detection circuit is simple and has fast response time ($\sim$ns), thus facilitates the packet switching operation.

B. Head Node and the Laser Transmitters

A centralized light source is resided at the head node, as shown in Fig. 8, to generate multiple wavelength channels. The simplest approach is to combine the output of many solitary single frequency lasers, such as the DFB lasers or external cavity lasers using fiber Bragg gratings as external mirrors. Integrated devices are also available, including the DFB laser array [15] or arrayed grating laser device with integrated active elements and feedback [16]. The main advantages of using integrated device are simple temperature control, and potentially low cost of packaging and simple in inventory. However, failure of individual element requires the replacement of the entire device. For dense WDM operation, the emission wavelengths have to be accurately controlled. Schemes based on interference [17] and referencing with a calibrated emission [18] were previously proposed. Optical power from the optical sources will also be monitored. Furthermore, enough redundancy (devices serving as backup) has to be implemented to ensure the performance of the network.

As shown in Fig. 8, the optical modulator is used to add the *Cycle-Start* flag, i.e., by adding an RF pilot tone of a specific frequency to the first time slot when a new cycle starts. Since each wavelength channel operates independently with each other, we need altogether N different RF tones for the N corresponding wavelength channels. The control of the addition of *Cycle-Start* flag is performed by the MAC unit, which obtains the network traffic information from all wavelength channels after a round trip on each bus.

C. Network Node Structure

The transceiver set of each network node is sandwiched by an optical amplifier pair. The amplifier located at the entry serves as the power booster while the one at the exit serves as the equalizer. Equalization is needed to avoid unequal amplification arising from channel dropping and adding among network nodes [19]. Fig. 9 shows our proposed implementation for the receiving and transmitting functions. The design is similar to the add–drop multiplexer of the wavelength routing network proposed in [20], but with a bank of optical modulators sandwiched by two AWG's. The optical modulators can be of interferometric Mach-Zehnder type or of electroabsorptive type. Other demultiplexing devices, such as those based on fiber Bragg gratings [21] can also be used.

As shown in Fig. 9, the incoming wavelength channels are demultiplexed by an AWG (AWG I). A fraction of the power at the wavelength assigned to that node for data reception will

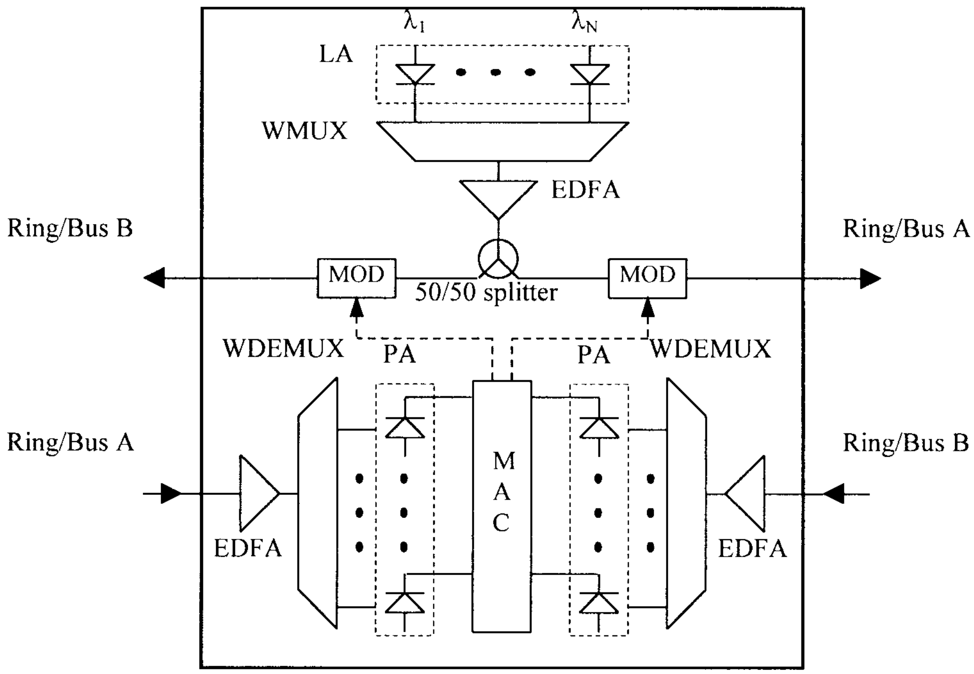


Fig. 8. Photonic implementation of the head-node. WMUX: wavelength multiplexer; WDEMUX: wavelength demultiplexer; PA: photodiode array; LA: laser array; MAC: media access control unit; MOD: optical modulator for encoding *Cycle-Start* (CS) flag.

be received. The remaining power of the dropped channel will be multiplexed with other wavelength channels and passed on to the next node. For the received signals, a low-pass filter is used to eliminate the RF pilot tones used for packet access signaling. Since the data encoding process can not be kept absolutely in synchronous between packets, data and clock recovery should best be retrieved at the packet level. Fast clock and data recovery circuit based on phase alignment [22] and burst mode receivers [23] can recover the clock within a few bits [23], [24].

For data transmission, all wavelength channels are demultiplexed at AWG I, and the availability of the time slots of the wavelength channel to the destined node is verified by the presence of the *Slot-Occupied* flag by tapping off a small fraction of the power. The corresponding RF switch for the destined wavelength channel will be closed, as controlled by the channel selection unit. Then, the presence of the *Slot-Occupied* flag and the *Cycle-Start* flag in each time slot will be detected. Such information is then used by the MAC unit to govern an RF switch (M-SW) where data will be forwarded to the corresponding optical modulator of the destined wavelength channel. Before sending out the data packets, they will be low-pass filtered and multiplexed with a locally generated pilot tone as a new *Slot-Occupied* flag for that time slot, thus avoiding data collision from the downstream nodes. Optical delay lines are inserted in between the fiber outputs of AWG I and the optical modulators to compensate for the electronic processing time in tone detection. All wavelength channels are equalized by an array of optical attenuators prior to AWG II. An interesting alternative is to use the dynamic wavelength equalizer in [25] to perform power equalization. After a round trip, the wavelength channels will be routed back to the head node where the cycle utilization for each wavelength channel will be computed. Such information is used by the MAC protocol to adaptively adjust the length of the next cycle in each wavelength channel.

IV. Network Performance

A. Bit Error Rate Analysis

The network size is largely limited by the accumulated noise generated from optical amplifier located at the entry and exit of each node. The bit error rate (BER) can further be degraded by the optical modulation index (OMI) imposed by the optical modulator. Consider the worst-case scenario where a wavelength channel is data-modulated at node #1 and received at node #M. At the output of each node, each wavelength channel is equalized to an optical power P_s. Neglecting the four-wave mixing effect, The Q-factor of the received data is shown in the equation at the bottom of the next page where $I_{1,0}$ and $\sigma_{1,0}$ are the mean detected photocurrent and total noise for ONE and ZERO bits, respectively, m is the optical modulation index at each modulator residing in each node, q is the electric charge, $R_{\rm res}$ is the receiver responsivity, $\sigma^2_{\rm th}$, $\sigma^2_{\rm ase}$, $\sigma^2_{s1\text{-ase}}$, and $\sigma^2_{s0\text{-ase}}$ are the thermal noise, ASE shot noise, signal-ASE beat noise at ONE bits, and signal-ASE beat noise at ZERO bits, respectively, given as below [26]

$$\begin{aligned}
\sigma^2_{\rm th} &= 4k_BTB_e/R\\
\sigma^2_{s1} &= 2qR_{\rm res}P_s(1+m)B_e\\
\sigma^2_{s0} &= 2qR_{\rm res}P_s(1-m)B_e\\
\sigma^2_{\rm ase} &= 2q^2n_{\rm sp}(G-1)B_oB_eM\\
\sigma^2_{s1\text{-ase}} &= 4qR_{\rm res}P_s(1+m)n_{\rm sp}(G-1)B_eM\\
\sigma^2_{s0\text{-ase}} &= 4qR_{\rm res}P_s(1-m)n_{\rm sp}(G-1)B_eM
\end{aligned}$$

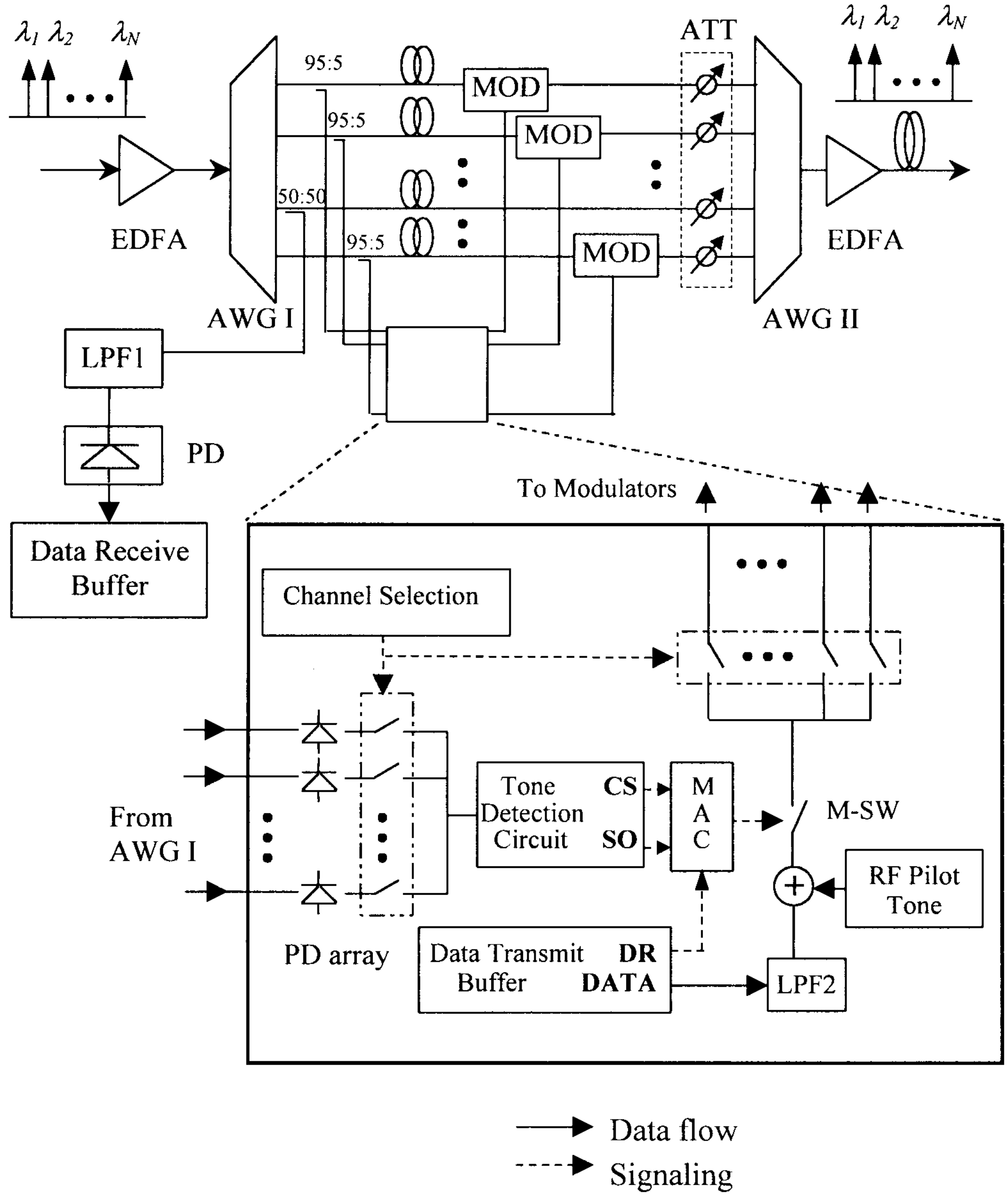


Fig. 9. Photonic implementation of a network node transceiver on one bus. MOD: optical modulator, EDFA: Erbium-doped fiber amplifier, PD: photodiode, AWG: arrayed-waveguide gratings, LPF: RF low-pass filter, ATT: tunable attenuators, MAC: media access control unit, CS: *Cycle-Start* flag, SO: *Slot-Occupied* flag, DR: "Data-Ready" flag, and DATA: data to be sent.

Here, G, B_o, B_e, $n_{\rm sp}$, R, and M are, respectively, the amplifier gain, optical bandwidth of the demultiplexer, receiver electrical bandwidth, spontaneous emission noise factor, receiver resistance and number of network nodes traversed. NRZ data modulation format is assumed. The bit error rate (BER) can then be obtained by evaluating

$$\mathrm{BER} = \frac{1}{2}\,\mathrm{erfc}\left(\frac{Q}{\sqrt{2}}\right)$$

Fig. 10(a) and (b) shows the predicted BER as a function of M for two different data rates 2.5- and 10-Gb/s, assuming the distance spacing between two nodes is fixed at 20 km with loss compensated by a 5-dB gain booster amplifier. The equalizer amplifier is also set at a moderate gain of 10 dB. B_e of the 2.5-Gb/s and data are 1.7-GHz and 6.5-GHz, respectively. Using a wavelength channel separation of 50-GHz, the number of nodes M supported by the scheme can be on the order of hundreds, depending on the OMI and choice of B_e. Constant BER of 10^{-9} and 10^{-15} are drawn for reference. Using a BER

$$Q = \frac{I_1 - I_0}{\sigma_1 + \sigma_0} = \frac{2mR_{\rm res}P_s}{\sqrt{\sigma_{\rm th}^2 + \sigma_{s1}^2 + \sigma_{\rm ase}^2 + \sigma_{s1\text{-ase}}^2} + \sqrt{\sigma_{\rm th}^2 + \sigma_{s0}^2 + \sigma_{\rm ase}^2 + \sigma_{s1\text{-ase}}^2}}$$

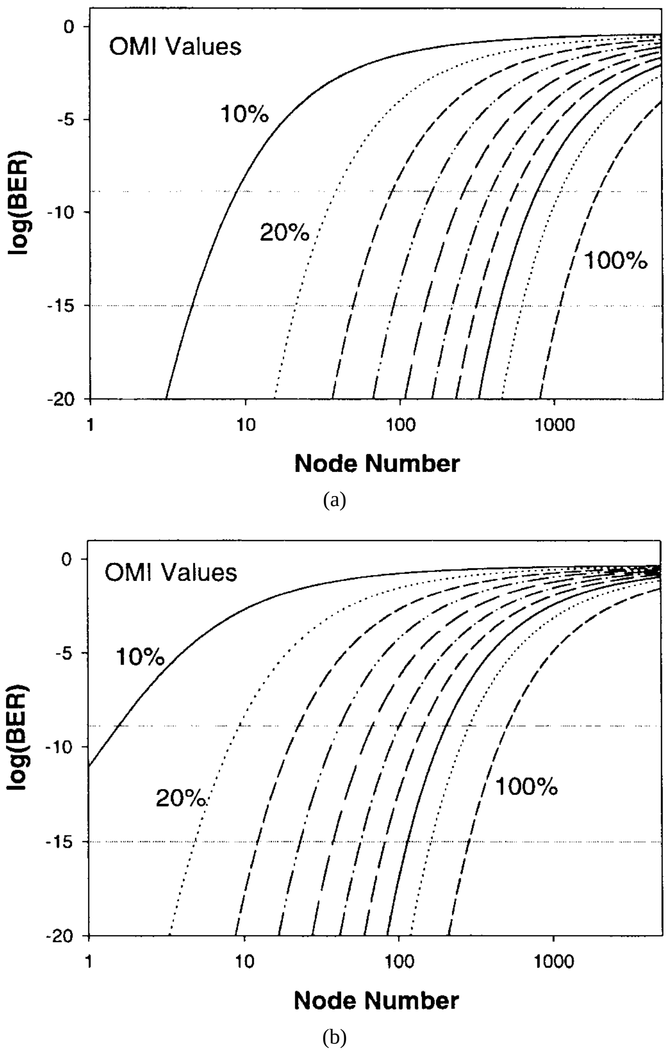


Fig. 10. BER analysis for different number of network nodes at different values of optical modulation index (OMI), when the data rate per channel is (a) 2.5-Gb/s; and (b) 10-Gb/s.

of 10^{-15} and an OMI of 90%, the network can support more than 200 to 1000 network nodes, each of which can be linked to another 100 workstations. The data rate to the desktop can be Gb/s, depending on the traffic conditions.

V. Experiment

Based on an experimental setup similar to Fig. 9, we have demonstrated the proposed network node with four data channels using a channel spacing of 100-GHz. The four WDM channels are located at $\lambda_1 = 1549.32$ nm, $\lambda_2 = 1550.12$ nm, $\lambda_3 = 1550.92$ nm and $\lambda_4 = 1551.72$ nm, conforming to ITU standard channel allocation grid. The wavelengths at λ_1 and λ_2 are generated by two DFB lasers while λ_3 and λ_4 are generated by two CW tunable laser sources. All four wavelengths are multiplexed by means of a 1×4-tree coupler and the resultant optical spectrum is shown in Fig. 11(a). To illustrate the packet access capability, λ_3 is externally modulated by a 622.08 Mb/s $2^{23} - 1$ PRBS NRZ baseband data stream multiplexed with a 1-GHz RF tone [Fig. 12(a)]. Prior being fed to the modulator, the baseband signals are chopped by a periodic square waves of 600-kHz such that λ_3 consists of alternate slots of modulated and unmodulated signals to simulate the input channel to the network node.

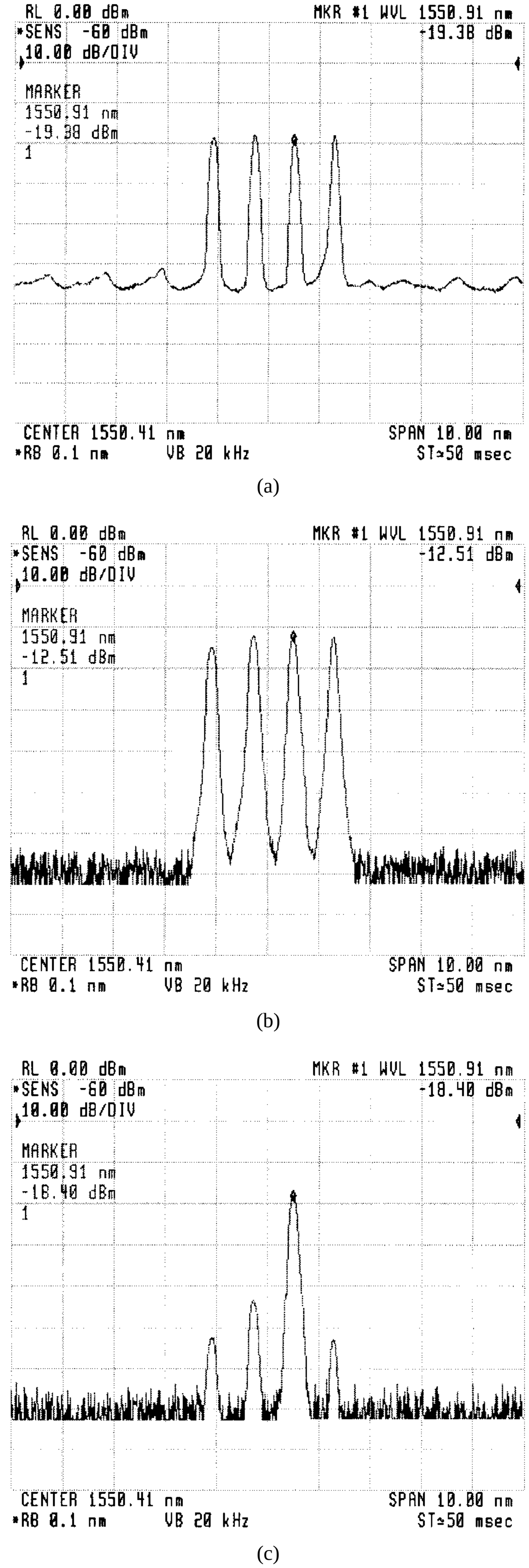
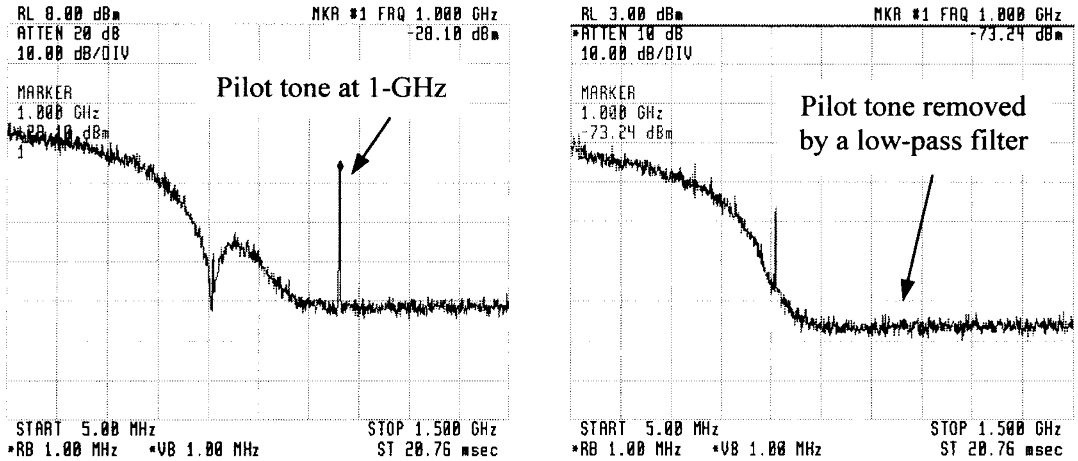
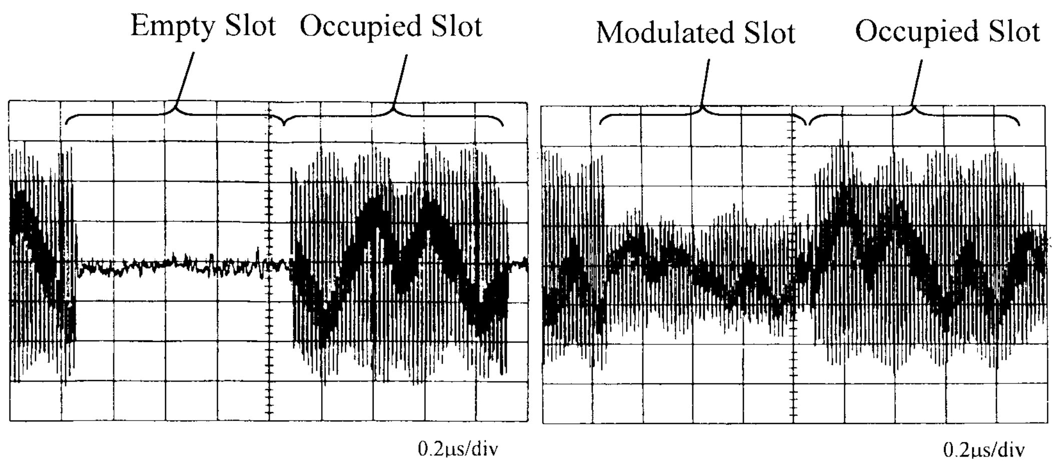


Fig. 11. Experimental results: Optical spectra at the (a) input to the network node; (b) output of the network node; (c) output of the network node showing the demultiplexed wavelength channel λ_3. The wavelength channels are spaced 100-GHz apart.



(a) (b)

Fig. 12. Experimental results: RF spectra of (a) a wavelength channel with slot occupied indication by the presence of a pilot tone at 1-GHz; data is filtered by a low-pass filter (3-dB bandwidth $= 640$-MHz) before being multiplexed with the pilot tone; (b) same wavelength channel measured at the detector but with the pilot tone removed by a low-pass filter (3-dB bandwidth $= 570$-MHz).



(a) (b)

Fig. 13. Recorded signal waveforms for channel λ_3. (a) Input at the node and (b) output of the node. An ac-coupled optical receiver is used in the measurement.

To input data on the available time slots on λ_3, 5% of the demultiplexed optical signal at λ_3 will be fed to the control processing circuitry for RF tone detection, while 95% of the signal will be directed to an optical Mach–Zehnder $LiNbO_3$ modulator through a fiber delay line of 100 m. Polarization controller is used to maintain the polarization. If there is no RF tone detected, the output of "Data Ready" (DR) is registered high and the switch (M-SW) will be closed for data injection from the local buffer. This is achieved by first low-pass filtering of the baseband NRZ data (LPF2, 3-dB bandwidth ~640 MHz), followed by multiplexing with a locally generated RF tone and fed to the optical modulator for data encoding on the available time slots. The four wavelengths are further power-equalized by variable optical attenuators and multiplexed again as shown in Fig. 11(b). To examine the data waveform, λ_3 is demultiplexed and detected [see Fig. 11(c)]. As shown in the figure, the pilot tone in the data is removed by a low-pass filter with a 3-dB bandwidth of 570 MHz [Fig. 12(b)]. The resultant received data waveforms are displayed in Figs. 13(a) and (b), showing the respective waveforms before and after the data sent from the network node. The apparent power fluctuations are due to insufficient sampling from the oscilloscope (bandwidth ~300 MHz). BER measurements (see Fig. 14) are performed with a 622.08 Mb/s $2^{23}-1$ PRBS NRZ continuous data stream at λ_3 for two cases: (a) pilot-tone multiplexed data are added to the unmodulated packet slots, and (b) continuous modulation with no packet adding. Both results indicate negligible power penalty.

VI. Summary

We have proposed a new node architecture and protocol for packet-switched WDMA metropolitan area data network. The network operates on a dual-bus topology and tunable-transmitter and fixed-receiver scheme is adopted to facilitate data multiaccess. The network protocol runs on a cycle mechanism and the cycle length can be adaptively changed according to the data traffic, thus provides high throughput. The photonic

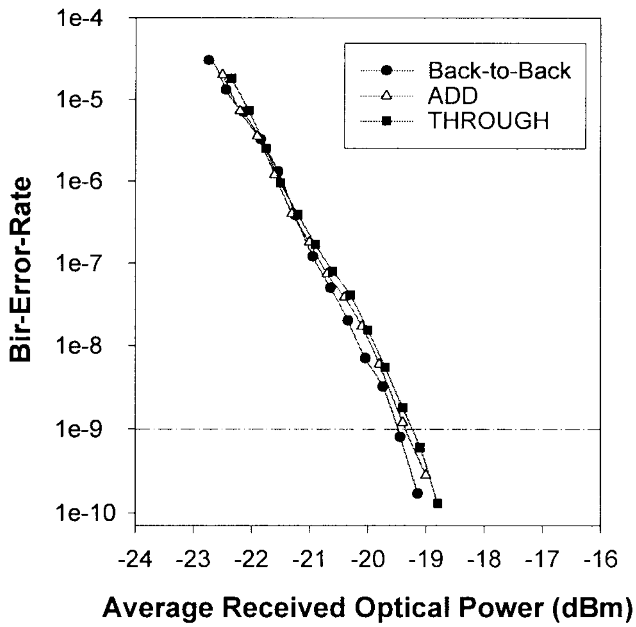


Fig. 14. BER measurements of the wavelength channel at λ_3 utilizing a 622.08-Mb/s $2^{23}-1$ NRZ PRBS. Back-to-back measurement (●, Back-to-Back); going through the network node (■, THROUGH), and data are added to the unmodulated wavelength channel from the network node (△, ADD).

implementation of the proposed network architecture and network nodes is discussed and a new packet-signaling scheme is proposed to avoid data collision during multiaccess. An experimental demonstration is also presented to show its feasibility.

ACKNOWLEDGMENT

The authors would like to thank R. Ho for helpful discussions and A. Siu for his technical assistance.

REFERENCES

[1] P. E. Green, L. A. Coldren, K. M. Johnson, J. G. Lewis, C. M. Miller, J. F. Morrison, R. Olshansky, R. Ramaswami, and E. H. Smith, "All-optical packet-switched metropolitan-area network proposal," *J. Lightwave Technol.*, vol. 11, pp. 754–763, May/June 1993.
[2] L. G. Kazovsky and P. T. Poggiolini, "STARNET: A multi-gigabit-per-second optical LAN utilizing a passive WDM star," *J. Lightwave Technol.*, vol. 11, pp. 1009–1027, May/June 1993.
[3] F. J. Janniello, R. Ramaswami, and D. G. Steinberg, "A prototype circuit-switched multi-wavelength optical metropolitan-area network," *J. Lightwave Technol.*, vol. 11, pp. 777–782, May/June 1993.
[4] E. Hall, J. Kravitz, R. Ramaswami, M. Halvorson, S. Tenbrink, and R. Thomsen, "The rainbow-II gigabit optical network," *IEEE J. Select. Areas Commun.*, vol. 14, pp. 814–823, June 1996.
[5] K. Nosu, H. Toba, K. Inoue, and K. Oda, "100 channel optical FDM technology and its applications to optical FDM channel-based networks," *J. Lightwave Technol.*, vol. 11, pp. 764, 776, May/June 1993.
[6] K. W. Cheung, "Adaptive-cycle tunable-access (ACTA) protocol: A simple, high-performance protocol for tunable-channel multi-access (TCMA) networks," in *Proc. ICC'93*, Paper 16.1, Geneva, Switzerland, 1993.
[7] T. H. Wu and R. C. Lau, "A class of self-healing ring architectures for SONET network applications," *IEEE Trans. Commun.*, vol. 40, pp. 1746–1756, Nov. 1992.
[8] C. K. Chan, L. K. Chen, F. Tong, and K. W. Cheung, "Realization of a time-slot access WDMA photonic dual bus/ring packet network node using centralized light sources," *IEEE Photon. Technol. Lett.*, vol. 9, pp. 1661–1663, Dec. 1997.
[9] I. Chlamtac, A. Fumagalli, L. G. Kazovsky, P. Melman, W. H. Nelson, P. Poggiolini, M. Cerisola, A. N. M. M. Choudhury, T. K. Fong, R. T. Hofmeister, C. L. Lu, A. Mekkittikul, D. J. M. Sabido IX, C. J. Suh, and E. W. M. Wong, "CORD: Contention resolution by delay lines," *IEEE Select. Areas Commun.*, vol. 14, pp. 1014–1030, June 1996.
[10] K. W. Cheung, "Acousto-optic tunable filters in narrow-band WDM networks: System issues and network applications," *IEEE Select. Areas Commun.*, vol. 8, pp. 1015–1025, Aug. 1990.
[11] H. Takahashi, S. Suzuki, K. Katoh, and I. Nishi, "Arrayed-waveguide grating for wavelength division multi/demultiplexer with nanometer resolution," *Electron. Lett.*, vol. 26, pp. 87–88, 1990.
[12] B. Malo, S. Theriault, D. C. Johnson, F. Bilodeau, J. Albert, and K. O. Hill, "Apodised in-fiber Bragg grating reflectors photoimprinted using a phase mask," *Electron. Lett.*, vol. 31, pp. 223–224, 1995.
[13] Y. H. Wang, L. K Chen, and K. W. Cheung, "Performance study of ACTA as an efficient high speed multi-channel integrated services network," in *Proc. ICC'97*, Montreal, Canada, 1997.
[14] IEEE P802.6/D12, "Distributed queue dual bus (DQDB) subnetwork of a metropolitan area network (MAN)," Feb. 1990.
[15] C. E. Zah, F. J. Favire, B. Oathak, R. Bhat, C. Caneau, P. S. D. Lin, A. S. Gozdz, N. C. Andreadakis, M. A. Koza, and T. P. Lee, "Monolithic integration of multiwavelength compressive strained multiquantum-well distributed feedback laser array with star coupler and optical amplifiers," *Electron. Lett.*, vol. 28, pp. 2361–2362.
[16] M. Zirnigbl, C. H. Joyner, C. R. doerr, L. W. Stultz, and H. M. Presby, "An 18-channel multifrequency laser," *IEEE Photon. Technol. Lett.*, vol. 8, pp. 870–872, 1996.
[17] F. Tong, K. P. Ho, T. Schrans, W. E. Hall, G. Grand, and P. Mottier, "A wavelength matching scheme for multiwavelength optical links and networks using grating demultiplexers," *IEEE Photon. Technol. Lett.*, vol. 7, pp. 688–690, June 1995.
[18] R. Boucher, B. Villeneve, M. Breton, and M. Tjtu, "Calibrated Fabry-Perot etalon as an absolute frequency reference for OFDM communications," *IEEE Photon. Technol. Lett.*, vol. 4, pp. 801–804, July 1992.
[19] C. S. Li, F. Tong, C. J. Georgio, and M. Chen, "Gain equalization in metropolitan and wide area optical networks using optical amplifiers," in *Proc. IEEE INFOCOM*, 1994, pp. 130–137.
[20] G. K. Chang, G. Ellinas, J. K. Gamelin, M. Z. Iqbal, and C. A. Brackett, "Multiwavelength reconfigurable WDM/ATM/SONET network testbed," *J. Lightwave Technol.*, vol. 14, pp. 1320–1340, June 1996.
[21] C. R. Giles and V. Mizrahi, "Low-loss add/drop multiplexers for WDM lightwave networks," in *Proc. IOOC'95*, paper ThC2-1, Hong Kong.
[22] D. Briggmann, G. Hanke, U. Langmann, and A. Pottbacker, "Clock recovery circuits up to 20 Gbit/s for optical transmission systems," in *Proc. Microwave Symp. Dig., IEEE MTT-S Int.*, 1994, vol. 2, pp. 1093–1096.
[23] A. Tajima, H. Takahashi, S. Araki, and N. Henmi, "A 10-Gb/s optical asynchronous cell/packet receiver with a fast bit-synchronization circuit," in *Proc. Tech. Dig., OFC'99*, San Diego, CA, Paper TuI6, Feb. 1999.
[24] M. Banu and A. E. Dunlop, "Clock recovery circuits with instantaneous locking," *Electron. Lett.*, vol. 28, no. 23, Nov. 1992.
[25] C. R. Doerr, P. Schiffer, L. W. Stulz, M. Cappuzzo, E. Laskowski, A. Paunescu, L. Gomez, and J. Gates, "Compact integrated dynamic wavelength equalizer," in *Proc. Postdeadline Papers, OFC'99*, San Diego, CA, Paper PD30, Feb. 1999.
[26] E. Desurvire, *Erbium-Doped Fiber Amplifiers, Principles and Applications*. New York: Wiley, 1994.

Chun-Kit Chan (S'93–M'97) received the B.Eng., M.Phil., and Ph.D. degrees in information engineering from the Chinese University of Hong Kong, Hong Kong, in 1993, 1995, and 1997, respectively.

In September 1997, he joined the Department of Electronic Engineering at the City University of Hong Kong, China, as a Research Assistant Professor. In June 1999, he joined the Photonic Networks Research Department of Bell Laboratories, Lucent Technologies, Holmdel, NJ, as a Member of Technical Staff. He worked on high-speed all-optical TDM and WDM tunable channel multi-access networks and fault surveillance techniques for optical network monitoring. His research interests include optical multi-access and transport networks, data networking, and optical network management.

Frank Tong (M'90–SM'95) received the Ph.D. degree from Columbia University, New York, NY, in 1987 with his dissertation work carried out at the Massachusetts Institute of Technology (M.I.T.) Lincoln Laboratories, Cambridge.

After graduation, he joined IBM Almaden Research Center where he worked on short wavelength lasers for optical recording. From 1989 to 1996, he worked on optical networking technologies under Paul Green at IBM T. J. Watson Research Center, Yorktown Heights, NY. He is currently an Associate Professor with the Information Engineering Department of the Chinese University of Hong Kong, China.

Dr. Tong has received many awards from IBM including the IBM Outstanding Innovation Award in 1995. He is a Fellow of the Insitution of Electrical Engineers (IEE).

Lian-Kuan Chen (S'86–M'92) received the B.S. degree from National Taiwan University, Taiwan, in 1983 and M.S. and Ph.D. degree from Columbia University, New York, NY, in 1987 and 1992 respectively, all in electrical engineering.

He worked at Jerrold Communication, General Instruments from 1990 to 1991. He has been engaged in research on lightwave video distribution systems with contributions in various distortion reduction schemes for different optical components. He joined the Department of Information Engineering, the Chinese University of Hong Kong in 1992. His current interests are in broadband local access, ultrahigh-capacity optical TDM/WDM networks, and the fault and performance management of optical networks; these projects are mostly supported by research grants of Hong Kong SAR government.

Kwok-Wai Cheung (SM'96) received the B.S. degree (First Honors) from the University of Hong Kong, Hong Kong, in 1978, the M.S. degree from Yale University, New Haven, CT, in 1981, and the Ph.D. degree from Caltech, Pasadena, CA, in 1987.

In December 1992, he joined the Chinese University of Hong Kong and is currently a full Professor in the Department of Information Engineering. In January 1996, he was appointed the founding Director of the Centre for Innovation and Technology (formerly the Information Networking Laboratories), a technology transfer organization for the Chinese University of Hong Kong. From 1987 to 1992, he was a Member of Technical Staff at Bell Communications Research, NJ. He has performed research in many areas, including lightwave system and device technology, high-speed network architectures and protocols, LAN/MAN and loop distribution networks, multimedia systems, and Internet/Web-based technologies. He has authored or coauthored about 100 journal and conference publications, and holds five U.S. patents.

Dr. Cheung was awarded an Electronics Letters Premium in 1992. He is a member of the Optical Society of America (OSA) and SPIE.

Eddie T. P. Kong was born in Hong Kong, Hong Kong, on April 7, 1971. He received the bachelors degrees in physical science and engineering physics from McMaster University, Hamilton, Ont., Canada, in 1994 and 1996 respectively. He received the M.Phil. degree in information engineering from The Chinese University of Hong Kong, China, in 1999.

Presently, he is part of the research staff in the Department of Information Engineering at The Chinese University of Hong Kong, where his research is concentrated on WDMA networks and monitoring of WDM networks.