A TUNABLE-CHANNEL MULTI-ACCESS WAVELENGTH DIVISION MULTIPLEXED NETWORK AND SURVEILLANCE SCHEMES FOR OPTICAL CROSS-CONNECTS

By

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Abstract

The ever-increasing strain on network bandwidth by bandwidth demanding applications such as high definition television (HDTV), Internet services, video-conferencing, and high-resolution medical imagery, has motivated much research effort to realize a practical high-speed optical multi-access network. In contrast to the conventional optical transmission systems that simply transmit data from the source to the destination, multi-access networks further allow resource sharing among all network nodes and support channel add-drop. Recently, remarkable progress in high-speed optical technology has been achieved so that optical switching is possible, eliminating the need for electronic switching. Therefore the electronic bottleneck is resolved and it becomes easier to realize a reliable high-speed all-optical multi-access network. This thesis explores a practical approach to achieving such a high-speed multi-access network and also investigates novel surveillance schemes for identifying optical path routing faults in optical cross-connects (OXC) for optically amplified wavelength routing networks.

In order to realize practical high-speed multi-access optical packet networks we focus on a class of multi-channel networks called tunable channel multi-access (TCMA) networks and propose a practical and feasible network structure that is suitable for high-speed photonic implementation. A wavelength division approach to TCMA is proposed and experimentally demonstrated. In the proposed wavelength division optical TCMA network architecture, an arrayed waveguide grating (AWG) is used to separate the wavelength channels. A modulator on each wavelength channel allows for fast channel selection. On each channel, slot access is achieved by our proposed pilot tone signaling scheme and data packets are modulated into empty slots. A previously proposed media access control (MAC) protocol, adaptive cycle tunable access (ACTA), is also considered

to support efficient multi-access on top of the proposed architecture. Therefore, our proposed TCMA network architecture with the ACTA protocol is considered feasible in realizing practical high-speed packet switched networks with fast channel tuning, efficient multi-access capability and excellent network performance.

A practical optical network should also be reliable and secure; thus we further consider fault surveillance in optically amplified wavelength routing networks. We propose and experimentally demonstrate two surveillance schemes for optical path routing fault identification in OXCs. They do not require any additional light source for monitoring. In one scheme, the residual unused amplified spontaneous emission (ASE) from optical amplifiers is used as the monitoring sources at each input fiber of the OXC. At each optical amplifier the ASE is modulated at a different low frequency that acts as the identification (ID) for that input port. Fiber Bragg gratings (FBGs) of different center wavelengths within the unused ASE region are placed at the output ports of the OXC to reflect the power of the modulated ASE to be analyzed. The second approach involves the addition of frequency tones onto wavelength channels as channel identification. At the OXC output ports, the channel ID is tapped off to compare the detected physical connection and the switch-setting information stored in the routing control module. Gain-saturated optical amplifiers are used for ID removal at the output ports of the OXC. In both cases, the optical path routing status of OXCs can be monitored simultaneously and continuously without interrupting the in-service data channels. Our proposed schemes may contribute to a complete fault surveillance system for future optical amplified wavelength routing networks.

摘要

在這個網絡帶寬的需求持續增長所形成的緊張情況下，高帶寬需求的應用如高清晰電視(HDTV)、互聯網服務、視像會議和高解像度的醫學圖像，將推動更多的研究，目的在實行一個實際的高速光學多址網絡。相對於傳統的光學傳送系統中，數據只是直接由起點傳送到目的地，多址網絡更加容許在傳網絡節點的資源分享和支援頻道增減。最近，在高速光學技術有突破性的進展，從而容許全光開關的實行，減少了電子開關的需求。所以解決了電子線路做成的瓶頸局限和更容易實行一個可靠的高速傳光多址網絡。本論文探究一個實際的方法來達致這個高速多址網絡，並研究嶄新的監視方案來確定在光放大波長分路網絡裏的光學互聯中光路分向的錯誤。

由於要實行高速多址光學模塊網絡，我們集中研究一種多頻道網絡級別稱爲可調頻道多址(TCMA)網絡，並提出了一個可行的網絡結構適用於高速光電子的實施。本文亦提出並從實驗中証實一項波長復用的取向來達成 TCMA。在這個提出的波長復用光學 TCMA 網絡的結構裏，一個陣式波道光柵被用於分開各波長頻道。在每一個波長頻道裏的調制器，容許快速頻道選擇。在每一頻道，用我們提出的時段選址信頭調信號的方法和數據模塊被調制於空的時段，來達成時段選址。較早前提出的媒介選址控制(MAC)協議和自適應循環可調選址(ACTA)也被考慮於支援較有效的多址在被提出的結構。所以我們提出選用的 ACTA 協議的 TCMA 網絡結構被証明可用於實行高速模塊交換網絡，並有快速頻號調控、有效的多址潛質和優良網絡表現。

在實際的光學網絡，應具備可靠和安全的條件。因此我們便進一步考慮在光放大波長分向網絡的錯誤監察。我們提出並實驗上証明二項可用於在 OXCs 中的光路分向錯誤確認的監察方案，這些監察方法不需要任何附加的光源。在其中的一個方案中，應用了從光放大器產生的剩餘放大自發輻射(ASE)來作爲在每個 OXC 中的光纖輸入的監察光源。在每一個光放大器中的 ASE 被調控在不同的低頻率來作爲每一入口的鑒別。在 OXC 的出口放置了不同中心波長的光纖布拉格光柵(FBGs)，其波長在不同的 ASE 範圍內，目的在反射已被調制的 ASE 來分析。另一個方案包括在波長頻道注入頻道調來作頻道的鑒別。在 OXC 的出口，一部分的頻道 ID 被取出來比較被測量的系統接合並在分路控制組件中儲存的交換設置信息。在增益飽和光放大器被用於去除在 OXC 出口的 ID。在以上二個情形，OXCs 中的光路分向的狀況可以在不需要干擾運作中的數據線路情況下作同時並連續的監察。我們提出的方法將有助於在未來光放大波長分路網絡中的完整錯誤監視系統。

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Chapter 1

Introduction

1.1 Optical Network Architecture

The expanding use of bandwidth demanding applications such as high-definition television (HDTV), Internet services, video-conferencing, and high-resolution medical imagery, has put a strain on present communication networks because of the bandwidth-limited electronic components they currently rely on. Therefore, future higher-speed networks will come to depend on optical technology, where the bandwidth of optical fibers can potentially reach more than 30 THz. Optical fiber properties of low signal attenuation, immunity to external interference, and suitability for high-speed interconnections without impedance matching, as required of electrical signals, are other factors that make optical networks the most attractive choice for future telecommunication networks [1].

Telecommunication networks consists of two network layers, a transport layer and an intelligent higher layer. The transport layer conveys user information while the intelligent higher layer supports enhanced service control and network operation functions. The transport layer of an optical network, as Figure 1.1 shows, is further divided into a circuit layer, a digital layer, an optical layer and a physical media layer [2]. The circuit layer provides the end-to-end connections (circuits) between service access

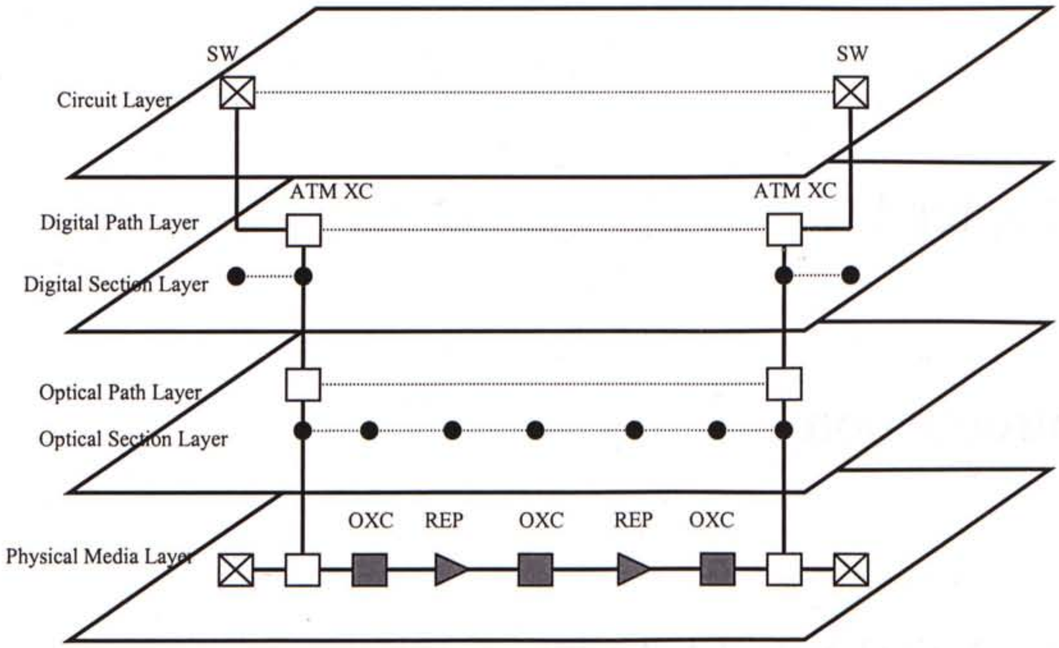


Figure 1.1: Transport layer structure of an optical network. SW: switch, ATM XC: ATM cross-connect, OXC: optical cross-connect, REP: repeater

nodes of the switching systems. The digital layer has a digital path sub-layer that routes and assigns a transparent path (a bundle of circuits) between circuit layer network nodes, and a digital section sub-layer that divides the network into sections to detect link or equipment failure. The digital path sub-layer can handle plesiochronous digital hierarchy (PDH) paths, synchronous digital hierarchy (SDH)/synchronous optical network (SONET) paths, and asynchronous transfer mode (ATM) virtual paths (VPs). The optical layer, similar to the digital layer, has an optical path sub-layer responsible for path routing and assignment, and an optical section sub-layer that divides the network into optical sections to facilitate the identification of faulty optical network equipment (NE). Optical cross-connects (OXCs) and optical add-drop multiplexers (OADM) allow reconfiguration of the optical path layer connectivity. The physical media layer is concerned with the actual fibers that connect nodes or subscribers. This layered structure allows the telecommunication network to be more reconfigurable, capacity upgradable and fault tolerant. Recently, much research has gone into accomplishing these functions in the optical layers.

1.2 High-Speed All-Optical Tunable-Channel Multi-Access Networks

It has been demonstrated recently that it is possible to transmit 3 Tb/s on a wavelength division multiplexed (WDM) channel [3]. But it is only a demonstration of a point-to-point data link and therefore does not meet the needs of future networks that will have to accommodate bursty data traffic from multiple users separated geographically. In this regard, an optical packet switching network is a probable solution. Also, optical switching removes the speed bottleneck imposed by electronic switches at network nodes. Three key issues need to be considered for a practical multi-access packet network: channel tuning; multiplexing and demultiplexing, and synchronization. Channel tuning of wavelengths requires either the transmitter or receiver to be tunable, keeping in mind the tuning time should be small compared to the data packet duration. Optical data needs to be multiplexed or demultiplexed at the precise channel, time slot for TDM and wavelength for WDM. At the receiver side, optical data generated from different transmitters are susceptible to dispersion and need to be synchronized. A wavelength-division approach previously proposed is experimentally demonstrated here at higher data rates in a 3-node network. All-optical techniques are employed to support high-speed operation. A previously proposed media access control (MAC) protocol, adaptive-cycle tunable-access (ACTA), is also considered to support efficient multi-access on top of the proposed architectures. Therefore, our proposed tunable-channel multi-access (TCMA) network architecture with the ACTA protocol are a viable combination in realizing practical high-speed packet-switched networks with fast channel tuning, efficient multi-access capability and excellent network performance.

1.3 Fault Surveillance of Optical Cross-Connects in Wavelength Routing Networks

In a WDM network a number of components may fail or degrade in performance. Fault surveillance schemes have been suggested for most of the components, such as the optical fiber links, EDFAs, and wavelength routers. The schemes help to facilitate the fault management function of network management by detecting and reporting any service outage immediately so that appropriate steps can be made to minimize data loss that may translate into a loss in business. Monitoring of the fiber links and network elements should be continuous and performed in-service without interrupting the data channels. The surveillance scheme should also encompass all possible dynamic situations that may develop in the network, such as adding and dropping of channels. We propose and demonstrate two novel in-service surveillance schemes that do not require any additional light source to identify routing faults in optical cross-connects (OXCs). They are shown to be very effective in implementing fault management in wavelength routing networks. The optical cross-connect is a key wavelength routing component in WDM networks that has been largely neglected in monitoring schemes. A failure or malfunction of the OXC will route streams of data to completely wrong destinations and lead to tremendous data loss. Optical path management schemes based on pilot tones and supervisory channels have previously been proposed, but these schemes sacrificed data transparency and privacy, and thus are intrusive in nature

In the first scheme, the residual unused amplified spontaneous emission (ASE) from optical amplifiers is used as the monitoring sources at each input fiber of the OXC. At each optical amplifier the ASE is modulated at a different low frequency that acts as the identification (ID) for that input port. Fiber Bragg gratings (FBGs) of different center wavelengths within the unused ASE region are placed at the output ports of the OXC to reflect the power of the modulated ASE to be analyzed. Thus any failure or incorrect physical connection at the switches can be detected at once by comparing the detected physical connection and the switch-setting information stored in the routing control module. Such information will be forwarded to the central office at once to report the failure.

The second approach to wavelength-routing monitoring in OXCs involves the addition of frequency tones onto wavelength channels as channel identifications (IDs). At the OXC output ports, the channel ID is tapped off to compare the detected physical connection and the switch-setting information stored in the routing control module. The system is also analyzed to determine the pilot tone removal requirement by EDFAs.

1.4 Outline of the Thesis

This thesis consists of five chapters. Chapter 2 provides an overview of all-optical networks and multi-access networks. Chapter 3 discusses a class of practical multi-access networks, called tunable-channel multi-access (TCMA) networks. The photonic implementation of a wavelength division TCMA network is proposed and experimentally demonstrated. The proposed architecture together with the proposed media access control (MAC) protocol, called adaptive-cycle tunable-access (ACTA), have great potential in achieving practical high-speed optical multi-access networks. Chapter 4 discusses the surveillance schemes for optical cross-connect (OXC) routing failure. The schemes do not require any extra light source for the monitoring signals. Though the main works of this thesis, presented in Chapter 3 and 4, seem unrelated they are both contributions to WDM networks in general. Chapter 5 summarizes this dissertation and suggests some future endeavors in both tunable-channel multi-access networks and optical cross-connects surveillance schemes.

Chapter 2

Optical Multi-Access Networks

Though WDM networks can access more of the bandwidth capacity of optical fibers, a considerable portion has yet to be fully utilized. This is because the electronics at the user level are not capable of operating at rates approaching that of the fiber bandwidth. So it is more efficient if several network nodes share the same resource, hence a multi-access network. This technique avoids the electronic bottleneck by processing the signals optically without any opto-electronic conversions. In a wavelength-division multi-access (WDMA) network, the shared resource is the wavelengths. In this chapter, the characteristics of all-optical networks and multi-access networks will be concisely presented in section 2.1 and 2.2 respectively. In section 2.3, some important considerations in the design of a practical optical multi-access network will be discussed.

2.1 All-Optical Networks

The ultimate goal of all-optical networks is to allow ultrafast optical signal processing so that some key network functions such as multiplexing and switching can be achieved at ultrahigh-speed. Therefore, the electronic bottleneck can be resolved and the realization of ultrahigh-capacity optical systems or networks of Gb/s or Tb/s can be made possible. The followings are some features of all-optical networks:

(a) Signal Transparency

All-optical networks are transparent to the protocol, signal format and the data bit rate since no electrical processing is involved. They can support a wide range of bit rates and protocols.

(b) Reduced Electronic Processing

Neither opto-electrical nor electro-optical conversion is required in all-optical networks to perform the common network functions such as routing and amplification. The reduced electronic processing circumvents the electronic bottleneck.

(c) Better Capacity Upgradability

High-speed networks require very stringent signal processing time. All-optical techniques can achieve sub-picosecond response time and thus support very high-speed and high capacity applications.

(d) Reduced Management

No interpretation or detection of data signal is needed during network management, thus avoiding the interruption to the data. So, the network management can be achieved in a simpler way.

(e) Direct Photonic Access

The key network functions such as channel add-drop, routing and switching can be achieved directly without demultiplexing all channels.

(f) Improved Reliability

Since much of the all-optical network is passive and unpowered, fewer components are subject to failure or degradation in performance.

Despite the above attractive features, there are still some difficulties in realizing a practical all-optical network. First, the optical components available nowadays are not yet mature and reliable. Their cost is very high and their reliability still needs to be improved. More improvement in technology is expected to resolve these issues. Second, in order to make the all-optical network viable, many design issues such as power equalization, wavelength reuse, synchronization and network management still require more extensive research to find the most feasible and optimal approaches.

2.2 Optical Multi-Access Schemes

In contrast to transmission systems that simply transmit data from the source to the destination, multi-access networks further allow resource sharing among all network nodes and support channel add-drop. Key network functions include routing, multiplexing, demultiplexing and switching. In order to facilitate the multi-access, the transceiver at each node should be channel-tunable and an efficient media access control (MAC) protocol is required to maximize the network throughput. Typical network elements include optical cross-connect (OXC), wavelength grating router (WGR), tunable filters, tunable transmitters and receivers, channel multi/demultiplexers and optical add-drop multiplexers (OADM).

Here are some examples of optical multi-access networks: MONET (Multi-wavelength Optical Network) [4], MWTN (Multi-wavelength Transport Network) [5], AON (All-Optical Network Consortium) [6, 7], ONTC (Optical Networks Technology Consortium) [8], RAINBOW [9], NTON (National Transparent Optical Network) [10], etc.

In the following subsections, three common kinds of optical multi-access networks, namely, wavelength division multi-access (WDMA), time division multi-access (TDMA), and subcarrier multi-access (SCMA) will be briefly described.

2.2.1 Wavelength-Division Multi-Access (WDMA)

In WDMA, wavelength channels are the shared resource. To access the network, each source node needs to first acquire a wavelength channel. There are two types of WDMA networks, namely single-hop WDMA networks and multi-hop WDMA networks. In single-hop WDMA networks, the data stream does not have any opto-electronic conversion before it reaches its destination. To ensure proper transmission to the final destination, they require wavelength-tunable devices, such as wavelength-tunable filters and lasers, to set up the network connections. In multi-hop WDMA networks, there are some intermediate nodes to relay the data stream from the source to the destination and thus they do not necessarily require tunable transceivers, but instead an efficient routing algorithm. However, opto-electronic conversions may be needed at the intermediate nodes, creating an electronic bottleneck. In general, both single-hop and multi-hop WDMA networks are susceptible to interchannel crosstalk, nonlinear effects, dispersion and optical amplifiers' ASE noise.

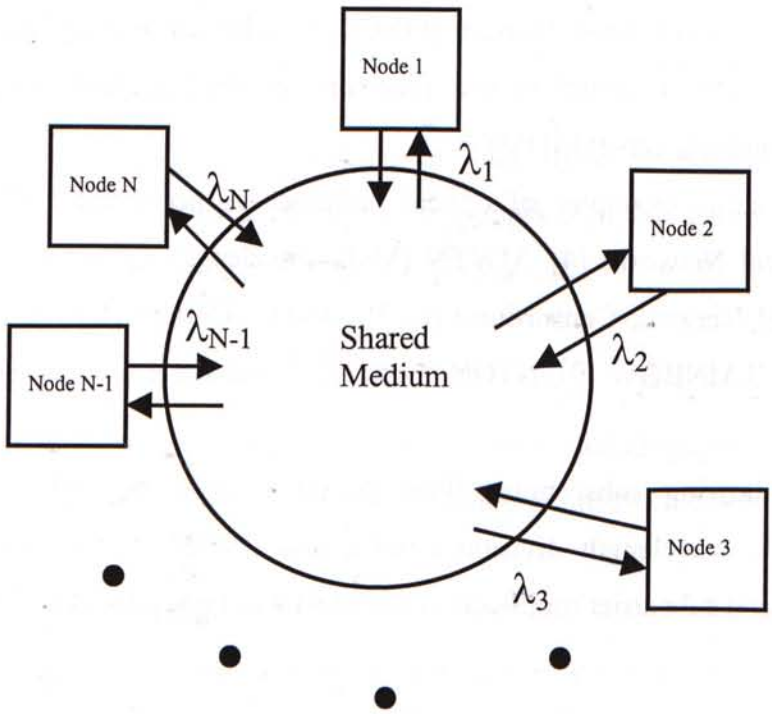


Figure 2.1: A wavelength-division multi-access network.

Four common types of WDMA networks are broadcast and select, static wavelength routing, dynamic wavelength routing, and wavelength conversion.

In broadcast and select networks, data from each transmitting node will be broadcast to all receiving nodes. Either or both the transmitter and receiver should be channel-tunable. Contention can be resolved by means of network protocols that coordinate the connections within the network.

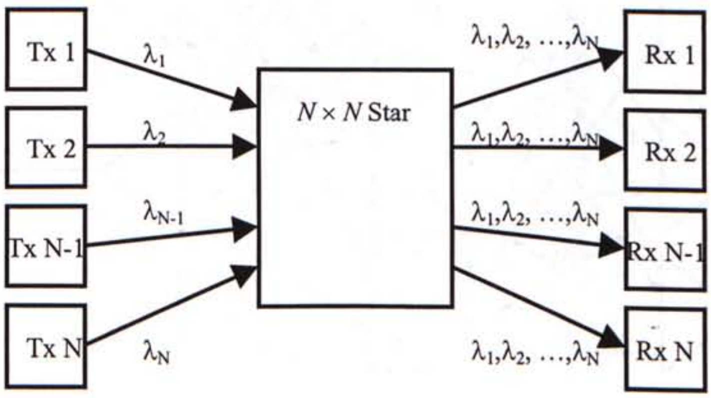


Figure 2.2: A broadcast and select network.

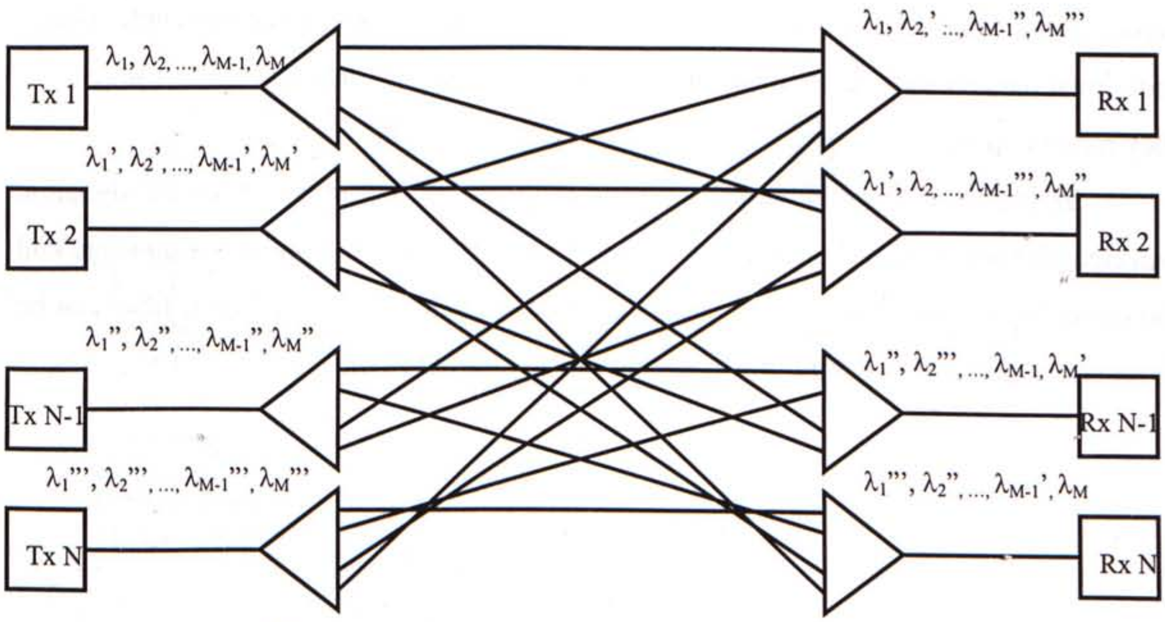


Figure 2.3: A static wavelength routing network.

In static wavelength routing, all wavelengths on each input fiber are routed to different output fibers depending on a routing matrix characterizing the router; this matrix is determined by the internal connections between the demultiplexing and multiplexing stages inside the router. The routing matrix is fixed and cannot be changed. The data packets on each wavelength are restricted to its own prescribed path.

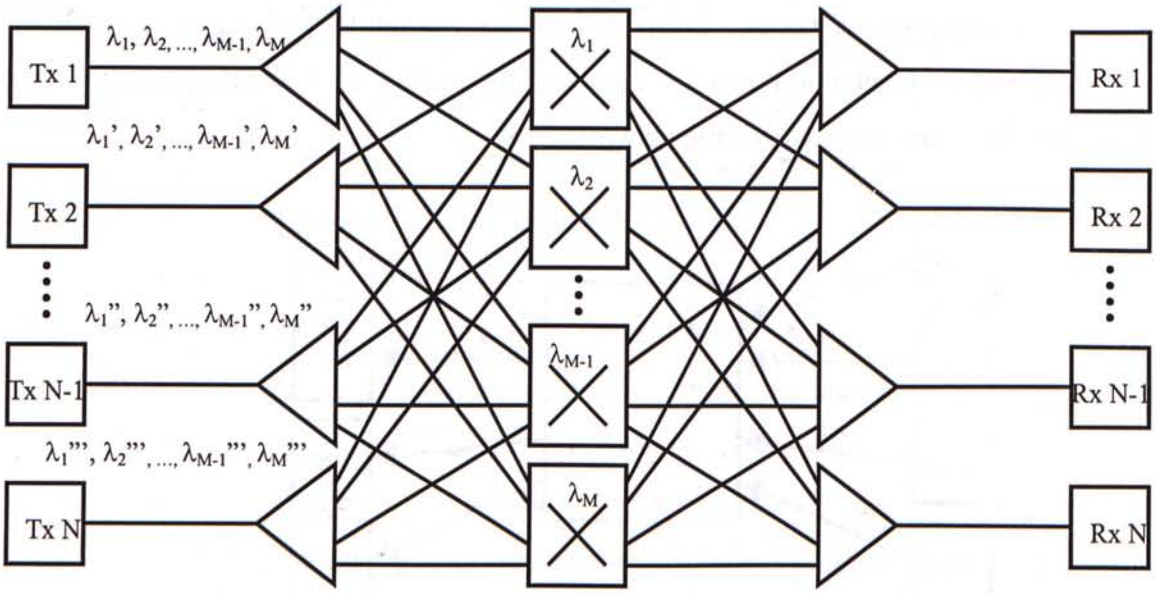


Figure 2.4: A dynamic wavelength routing network.

In dynamic wavelength routing, the routing path of each input wavelength can be reconfigured on demand by means of electronic controlled optical space switches. Thus, individual data packets on each wavelength can travel through different paths, though they remain on the same wavelength.

In order to resolve wavelength contentions at the output port of dynamic wavelength routers, wavelength converters are added between the multiplexing stage and the optical space switches. In this way, any input wavelength on any input fiber can be cross-connected with any output wavelength on any output fiber.

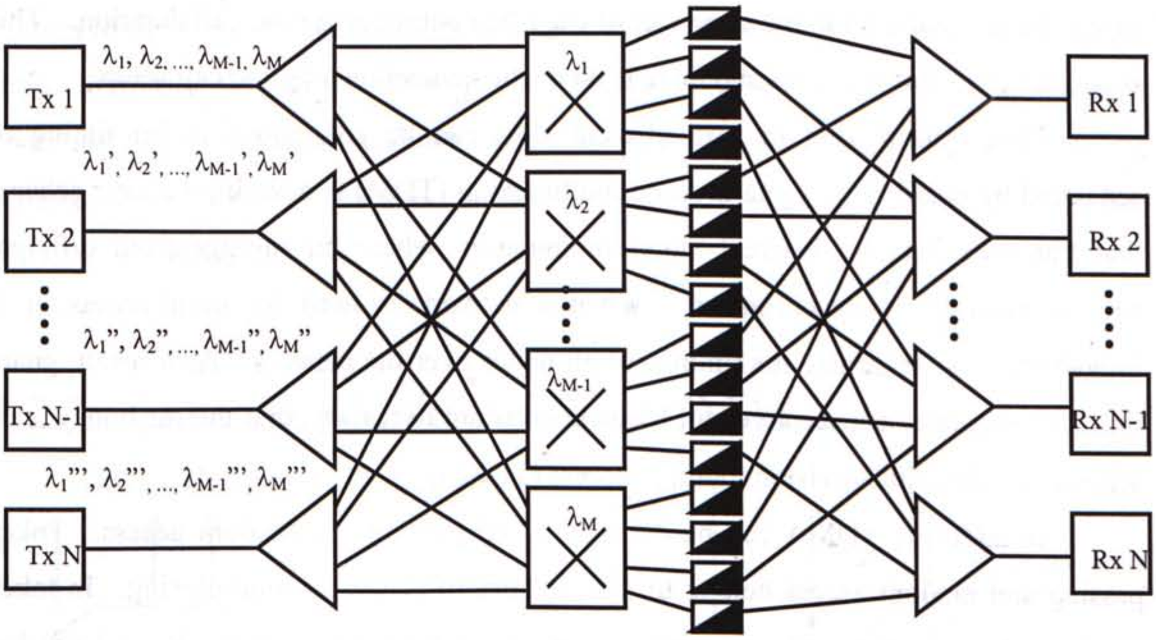


Figure 2.5: A wavelength converting network.

2.2.2 Time-Division Multi-Access (TDMA)

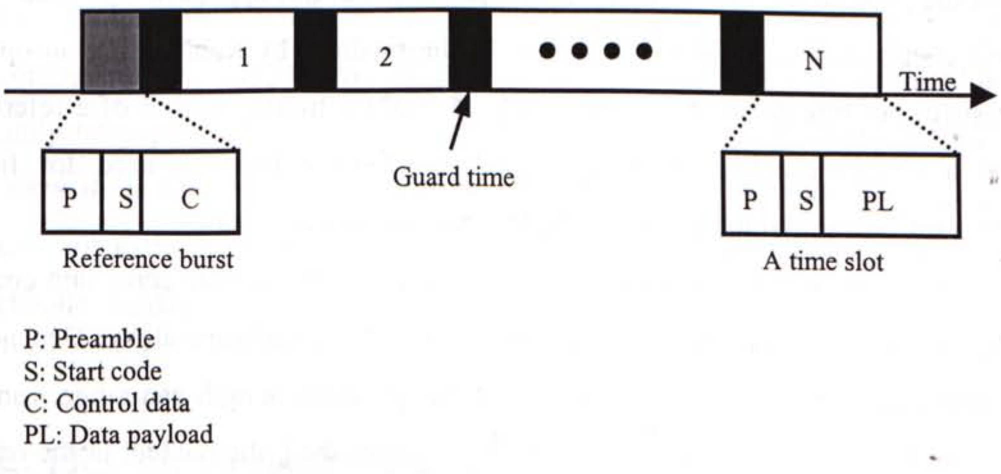


Figure 2.6: A time-division multi-access frame.

In time-division multi-access networks (TDMA), a single wavelength is used and the time is divided into frames, and each frame is partitioned into a certain number of timeslots, as shown in Figure 2.6. The communication nodes share the same medium by sending data in different slots. Once a slot is allocated during the call setup, a node can repeat the transmission in the same slot of each frame throughout the call duration. This is called deterministic access and there is no traffic contention after the call setup.

Data transmission in two adjacent slots can be continuous in bit timing or separated by guard time. Time division multiplexing (TDM) is a medium access scheme that transmits data in different slots continuously, where bit timings from different sources need to be synchronized. When a network is used for multi-access, it is impossible to synchronize the timings of all nodes over the network. As a result, guard time that separates consecutive slot transmissions are necessary, and the medium access scheme is called time division multiple access (TDMA).

In addition, TDMA can be done by token passing and random access. Token passing and random access belong to the category of statistical multiplexing. In token passing, a transmission node can send data only when it holds the token. When it finishes transmission, it passes the token to the next node. An important token-passing fiber-based local area network is called the Fiber Distributed Data Interface (FDDI). To support TDM traffic that requires deterministic access, a hybrid version called FDDI-II has also been defined. In random access, an optical transmission version of carrier-sense multiple access with collision detection (CSMA/CD) has been proposed. However, because of the poor access efficiency from collisions, use of this approach is limited.

An optical transmitter in TDMA gets access to the medium by transmitting an optical burst consisting of binary bits over a timeslot. A TDMA frame consists of a reference burst and a certain number of timeslots. The reference burst is used for frame synchronization and signaling, and the timeslots are used to carry data.

The reference burst consists of three parts: a preamble, a start code, and control data. The preamble is a periodic bit sequence for bit timing synchronization. Depending on how rapid a synchronization can be achieved, the preamble length can range from 10 to several hundred symbols. Once the bit timing is established, the content in the rest of the reference burst can be read. Following the preamble is a unique start code indicating the end of the preamble and the start of the information portion of the reference burst. By recognizing the word, control data can be interpreted correctly. In general, control data carries information such as station timing, call setup status, and signaling information.

The reference burst in a TDMA frame is the overhead and occupies only a small portion of the frame. The rest of the frame is divided into timeslots separated by guard time. Similar to the reference burst, each time slot consists of preamble, a unique start code, and the information payload. Because of different propagation delays between stations, the guard time between timeslots is necessary to avoid overlap between two consecutive time slots.

2.2.3 Subcarrier Multi-Access (SCMA)

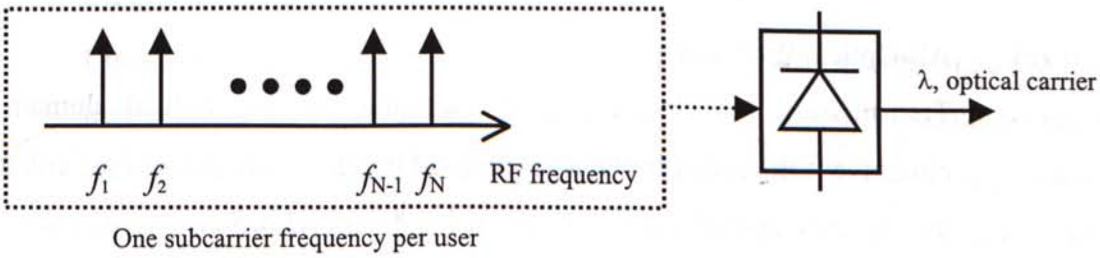


Figure 2.7: Subcarrier multi-access.

In subcarrier multi-access networks (SCMA), a single wavelength is used and each channel is represented by a specific RF subcarrier. Subcarrier multiplexing (SCM) is used to combine all channels on the backbone. The RF technology is quite mature and the components are inexpensive and have good stability. However the signal processing can only be implemented in the electrical domain, introducing a bandwidth bottleneck. The capacity is also limited by various kinds of noises such as thermal noise, shot noise, relative intensity noise (RIN), intermodulation products, clipping and optical beat interference (OBI).

2.3 Design Considerations

In order to realize a practical optical multi-access network, the following issues should be considered in the network design.

(a) Network Topology

The network topology determines the node connectivity, network reconfigurability, power budget, dynamic range, and network capacity.

(b) Media Access Control

There are two types of medium-access control: multiplexing and multiple access. Each of these can be implemented through wavelength division, time division, subcarrier, or code division. The selected mode or combination of modes determines how a transmission node sends data to the shared medium, which has a much higher speed than the user data rate.

(c) All-Optical Processing

Transmission, multiplexing, and switching in the optical domain can circumvent the speed bottleneck imposed by electronic processing, enhancing the capacity upgradability. Simplified and parallel processing are other ways to solve the speed bottleneck when electronic processing is a must.

(d) Switching Speed

Channel multiplexing and demultiplexing requires fast switching speed in high-capacity optical networks. Photonic switching is preferred because it can avoid the electronic bottleneck in two ways. It eliminates the need for electronic-to-optic and optic-to-electronic conversions, and maintains the high bandwidth optical signals within a medium that can support their bandwidth requirement.

(e) Channel Accessibility

In order to perform multi-access, each network should be capable of accessing one or more channels to send or receive data. There are three types of node configuration: (i) fixed-tuned transmitter and tunable receiver (FTTR), (ii) tunable transmitter and fixed-tuned receiver (TTFR), and (iii) tunable transmitter and tunable receiver (TTTR). Of course configuration (iii) provides the best connectivity and flexibility but it requires very costly tunable devices in both transmitter and receiver. The tuning time of the devices should be in the order of micro- or nano-seconds in order to support high-speed operation.

(f) Timing and Synchronization

Timing and synchronization are quite important in transmission, detection and multiplexing of multiple data channels. They are especially stringent in time-division multiplexed systems and in optical processing.

(g) Control Signaling

Control signaling is required in network management so that the status of the network and the resources can be monitored. The schemes should be non-intrusive and allow in-service operation. For example, fault management is needed to avoid or resolve a disastrous situation while the performance management is required to ensure the quality of service. In addition, control signaling is also required in coordinating the channel tuning mechanism of the transmitters and receivers on the network. A common approach is to use subcarriers or pilot-tones to carry the routing and channel tuning information.

(h) Protocols

Protocols are required to coordinate the access of the shared network resources and the connection setup among all network nodes to achieve the most efficient multi-access. The throughput, delay and fairness issues should be considered. Suitable protocols can substantially reduce the complexity of implementing all-optical networks.

(i) System Limitations

Some transmission limitations such as dispersion, nonlinear effects, crosstalk, noise, and power budget should be carefully considered since they will reduce the capacity limit.

(j) Node Complexity

The complexity of all network nodes should be kept as simple as possible to reduce the cost and facilitate the signal processing at the nodes. A class of tunable-channel multi-access (TCMA) networks can simplify the node complexity. They allow all network nodes to operate only at channel rate while being capable of accessing the aggregate network capacity.

Chapter 3

All-Optical Tunable-Channel Multi-Access Networks

It has been anticipated that future broadband services will require large amounts of data exchange. Therefore it is essential for future networks to have efficient network protocols and architectures that can support real time and high bit-rate services as well as technologies that can allow high-speed data processing and transmission. To realize ultrahigh-speed networks, optical technology is considered more promising than electronics due to the limited bandwidth of electronic components. It has been demonstrated recently that it is possible to transmit 3 Tb/s on a wavelength division multiplexed (WDM) channel [3]. However, the demonstration was a fixed point-to-point transmission link, and will not meet the needs of future networks that will have to accommodate bursty data traffic from multiple users separated geographically. In this regard, an optical packet switching network is a more viable solution. Tunable-channel multi-access (TCMA) networks are very attractive in realizing ultrahigh capacity packet switching networks. This is a class of multi-channel networks that employ local channel tuning to reduce the node complexity as well as the clock recovery speed. All components at each node are required to operate at the node speed only. In order to realize a practical multi-access packet network, channel tuning, multiplexing and demultiplexing, and synchronization issues need to be considered.

In any network, either the transmitters or the receivers have to be tunable. The channel tuning time should be shorter than the duration of a data packet. The optical data needs to be multiplexed or demultiplexed at the precise channel, time slot for TDM and wavelength for WDM. At the receiver side, optical data generated from different transmitters are susceptible to dispersion, and need to be synchronized.

In this chapter, we present the network architectures and protocols for TCMA networks in section 3.1 and section 3.2 respectively. In section 3.3, a wavelength-division TCMA network is proposed and implemented. A 3-node WDMA network with time-slot access capability and simple subcarrier signaling is realized.

3.1 Tunable Channel Multi-Access (TCMA) Networks

To achieve high-speed networking, both scalable capacity and low node complexity are critical design issues. Tunable-Channel Multi-Access (TCMA) networks is a generic class of multi-channel networks that meets these two requirements. Each node receives information from a designated channel. It can also send information to the other nodes by writing to the appropriate channel that the destined node is attached to. Since each channel operates at a lower data rate whereas the multiplexed data stream has a much higher data rate, the node complexity is much reduced while the network capacity is increased by a factor of M, where M is the number of channels.

TCMA networks can be implemented using ring or bus topologies. In our design, the physical network is assumed to be a dual-bus looped back to itself. Fixed-sized empty slots are continuously generated from the Head-of-Bus nodes in opposite directions. Each node consists of two receiving modules and two transmitting modules, one for each bus. The receiving modules are permanently connected to designated channels whereas the transmitting modules can be tuned to any output channel. The proposed TCMA network architecture can be implemented in several common multiplexing schemes such as time-division-multiplexed (TDM) [11], wavelength-division multiplexed (WDM) [12] or subcarrier multiplexed (SCM) [13].

In contrast to the traditional transmission systems, a network should possess multi-access capability. Thus an efficient media access control (MAC) protocol should be employed. A previously proposed protocol, the Adaptive Cycle Tunable Access

(ACTA) [14], was shown to have good characteristics such as a simple design, high throughput, low delay, and performance that is independent of the round-trip delay in bus/ring topologies. The throughput fairness can be maintained to within a factor of two even under heavily-overloaded conditions. Therefore, a TCMA network with the ACTA protocol is a feasible and desirable approach to realizing a practical integrated packet-switched network with fast channel tuning, efficient multi-access capability and excellent network performance.

3.2 Protocols for TCMA Networks

Many existing network protocols can easily be adapted to work with TCMA networks, such as Fasnet and its derivatives [15,16]. However, these protocols and many others that employ a cycle mechanism have a performance dependent on the round-trip delay time of the network. The Adaptive-Cycle Tunable Access (ACTA) protocol [14], which has been shown to be a very efficient protocol, has been proposed for media access control of such high-speed all-optical networks [11].

Basically, ACTA follows a cycle mechanism with slotted access. The cycle length, corresponding to the number of time slots in a cycle, can be adjusted according to the traffic load of individual nodes so as to improve network utilization and throughput fairness for all network nodes. Network simulations have been performed which demonstrate that a normalized throughput of > 0.9 per channel can be achieved (with a controlled load equals 0.95) and the fairness can be maintained to within a factor of two even under heavily overloaded conditions. Therefore, TCMA network with ACTA protocol provides a flexible and efficient platform for ultrahigh-speed networking. We will present the advantages of ACTA and the media access procedure in the following.

Advantages of ACTA Protocol

There are several advantages of ACTA over other protocols. The first advantage is its simplicity. Unlike DQDB [17], no request registration is required. Local processing is kept to a minimum; media access can be decided from simple state transitions based on slot information. 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; re-assembly of large packets is simplified. Second, the performance is independent of the round trip delay time. The normalized throughput can approach unity and the throughput 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 non-uniform traffic conditions and does not have pathological problems such as lock out in 2-node competition situations that affect many other protocols.

Media Access Procedure for ACTA Protocol

Each transceiver pair at each node has two packet buffers, one for the transmitter and the other for the receiver. For reception, the network node reads in the packet from its channel at current time slot when the destination address of a packet in that slot matches its own address. For transmission, the media access procedure contains two phases: (1) channel tuning, and (2) channel access.

In the channel tuning phase, the transmitting module is tuned to the channel that the destination node is connected to. In the channel access phase, it will follow the following procedure to write data onto the available slots:

1. Fixed-sized empty slots are continuously generated from the Head-of-Bus nodes in opposite directions. Each slot has two control-status bits: Cycle-Start and Slot-Occupied.
2. Variable-length cycles, each containing a certain number of empty slots, are continuously generated from the Head of Bus with a length set by cycle length counter.
3. At the start of a cycle, Cycle-Start of the first slot is set by the Head-of-Bus.
4. Any intermediate node can write consecutively onto the first N_q available slots immediately after it has seen Cycle-Start. N_q is an arbitrary quota decided for

each node in advance according to priority. For simplicity it can be taken as a constant.

5. Slot-Occupied is set after a slot has been written onto.
6. When a node encounters one of the following conditions during transmission, it must stop and wait for the next Cycle-Start for any further transmission:
   (a) the node has used up its quota of N_q slots in the current cycle;
   (b) the node encounters a packet going to a different channel;
   (c) the outgoing queue has been depleted;
   (d) there are no more available slots in the current cycle.

   The transmission quota is reset to N_q for the new cycle.

7. The End-of-Bus node computes the new cycle length according to the utilization of the current cycle using an adaptive algorithm. The cycle-length is always bounded by a minimum and a maximum. The new cycle-length is stored into the cycle-length counter.
8. After the current cycle has been completed, the Head-of-Bus node initiates a new Cycle-Start with a cycle-length given by the cycle-length counter. If an open dual-bus is used instead of a looped bus, the information about the new cycle-length can be sent back from the end-node to the Head-of-Bus via the opposite bus.

It can be seen that the media access is extremely simple and requires nothing more than a few state transitions and counting the number of packets sent in a cycle.

Cycle Utilization & Adaptive Algorithm

The following simple adaptive algorithm has been found to work very well for ACTA:

$$new\ cycle\ length = \frac{current\ cycle\ length \times cycle\ utilization}{controlled\ load\ L_C}$$

where *cycle utilization* is the number of slots used in the cycle divided by the cycle-length, and *controlled load* is a parameter specifying the desired throughput under heavily overloaded conditions. When the network load deviates from the control load L_c, the cycle length should expand or contract accordingly, trying to maintain the network utilization close to the controlled load.

Even though it is tempting to try to get the largest possible throughput by setting the controlled load very close to unity, it must be prevented because the adaptive mechanism would lose its ability for cycle expansion. Also, it takes a long time for the network to adapt to a higher network load.

The flexibility of ACTA can be seen in the following example. When only a single node is transmitting on the channel, the cycle utilization is low since other nodes are not using their quota N_q. The ACTA protocol will reduce the cycle length until the cycle utilization equals to L_c. This means the channel utilization by the single node can be increased from $1/N \times L_c \times$ *channel capacity* (assuming uniformly loaded) to $L_c \times$ *channel capacity*; a factor of N increase where N is the number of nodes per channel.

3.3 Photonic Implementation of a Wavelength-Division TCMA Network with Time-Slot Access

In this section, we will investigate a wavelength division multi-access (WDMA) implementation of a TCMA network. My contribution to this proposed network architecture is the implementation of a 3-node network. This includes the design, fabrication, and testing of the pilot tone detection circuit for time slot accessing. Details on node interconnection and source organization will be examined before revealing the approaches taken in our proposed network.

For WDMA networks, interconnection between nodes can either be configured with tunable transmitter and fixed-tuned receiver (TTFR), or fixed-tuned transmitter and tunable receiver (FTTR). For the TTFR case, each node is assigned with a fixed wavelength for receiving data. 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 channel i (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 channel *j* (λ_j), for data reception. This adds extra complexity in control signaling and effectively reduces the throughput and efficiency of the network. Another problem in FTTR is that receiver contention occurs when data arrives simultaneously at the same node from more than one transmitting node. A possible solution to such problem is to use switched delay lines [18]. In our network, we adopt the TTFR scheme to eliminate the receiver contention problem, where "tunable transmitter" refers to wavelength selection at the transmitting node not the actual wavelength tuning of a laser source. We also employ a new and simple packet access-signaling scheme to avoid data collision during transmission.

Most WDMA networks [19] employ a decentralized light source approach in which an individual laser transmitter of assigned fixed wavelength is installed at each network node to add data into the network. However, decentralized light-source approaches suffer from the wavelength-matching problem. The added and dropped wavelengths at the network nodes may not coincide exactly, as generating identical wavelengths from two different sources is difficult. This wavelength deviation causes degradation and crosstalk in the demultiplexing and the detection processes at the subsequent network nodes. Networks with centralized sources, in which all the network nodes (other than the head node) transmit their data on wavelength channels generated at the head node, can be an attractive alternative especially for dense WDMA networks in which the wavelength separation is very small [13]. An added advantage of having centralized light sources is the ease of control and maintenance as all the light sources can be monitored simultaneously at one site. In our network, we chose to use a head node with a centralized light source that emits multiple and equally spaced wavelengths simultaneously on each bus to be shared among all network nodes to perform data communications within the network. 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 with modulation speed of 2.3 Gb/s.

In this section, we propose and realize a time slot access, wavelength division TCMA packet network using TTFR approach with centralized light sources and simple control signaling [20]. The centralized light source can be a laser array with a different emission wavelength from each array element or simply an assembly of solitary laser transmitters with different emission wavelengths. The tunable transmitter refers to wavelength selection at the transmitting node. To improve the channel utilization, each wavelength channel can further be partitioned into different time slots. The simple and efficient time-slot access ACTA protocol [14] is used to ensure a fair share of a wavelength channel among network nodes. We also use a single RF pilot tone, multiplexed with the data modulated at baseband, to signify the occupancy of a time slot. Control signaling schemes using multiple RF subcarriers or pilot tones have been proposed previously [21]-[26], but these require complicated demodulation processes and electronic circuitry. Moreover, the number of required RF subcarriers depended on the number of nodes in the network.

3.3.1 Proposed Network Architecture

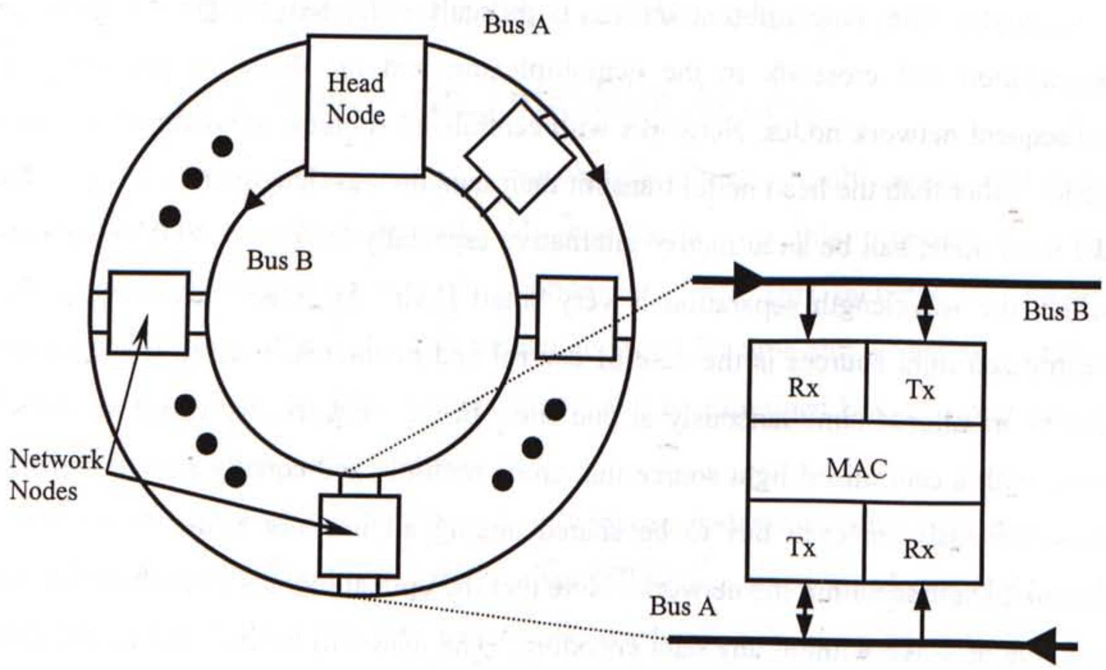


Figure 3.1: Dual Ring/Bus network architecture. Inset shows the basic configuration of a network node. Rx: receiver, Tx: Transmitter, MAC: media access control.

The proposed network architecture is shown in Figure 3.1, consisting of one head node and many network nodes arranged in a dual counter-propagating looped-back bus configuration, is the same as the TCMA network with TTFR approach discussed previously. The head node, as shown in Figure 3.2, generates multiple wavelength channels with empty slots (unmodulated time slots with CW optical power) as shared channels. Each network node may serve as a router to a 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 [27]. In addition to high efficiency and throughput, the dual looped-back bus configuration can also enhance the networks' survivability in case of node failure or fiber break. The network node next to the failed node or fiber will route all traffic from

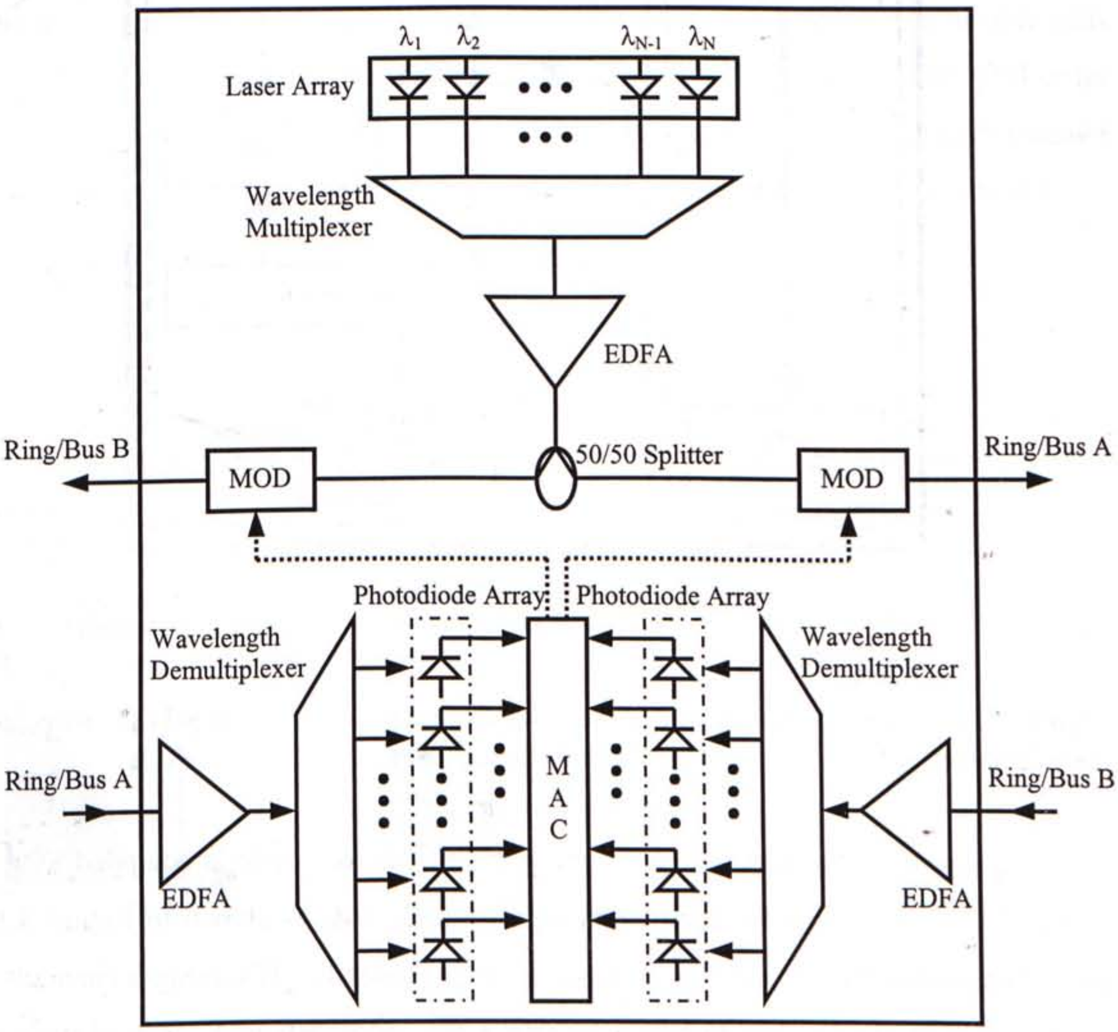


Figure 3.2: Photonic implementation of the head-node. MAC: Media access control unit, MOD: optical modulator for encoding "Cycle-Start" (CS) flag.

one ring back to the other, thus generating two independent rings similar to the self-healing feature [28] 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 a partial failure of an optical amplifier attaching to a node, and thus appropriate remedies can be made promptly.

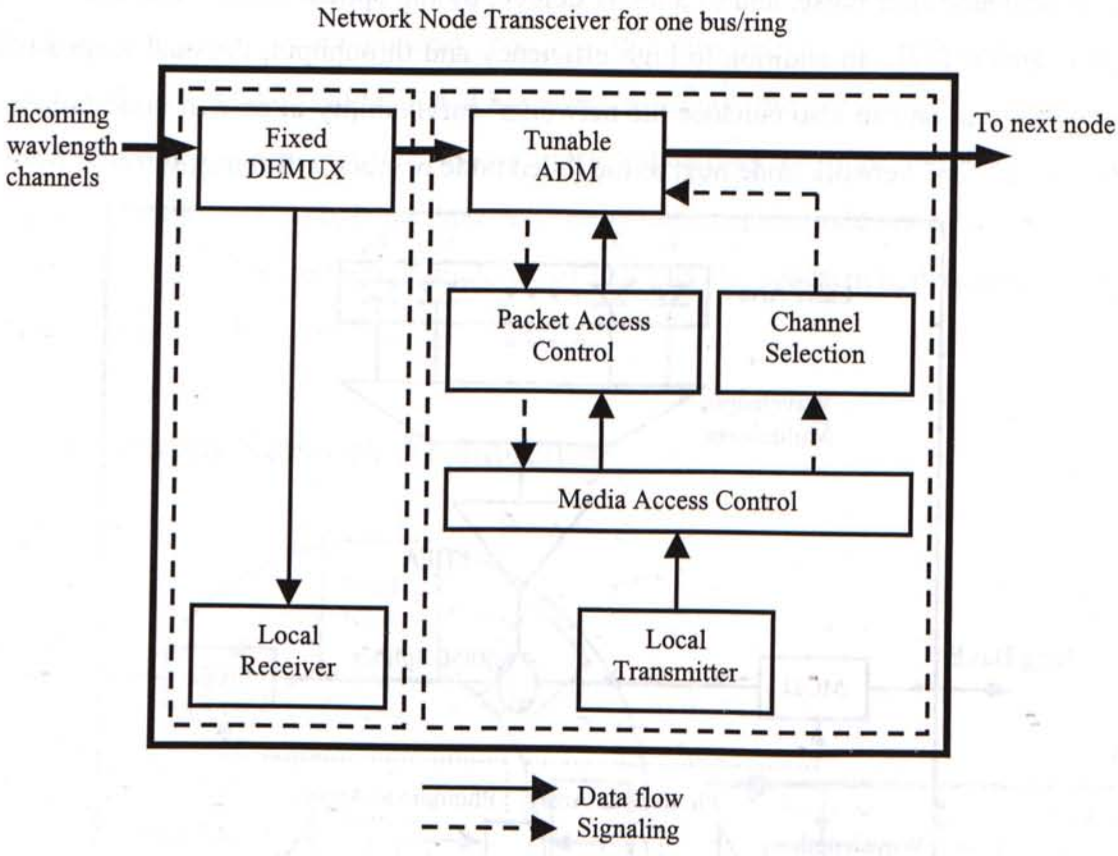


Figure 3.3: Architecture of a network node transceiver. DEMUX: wavelength demultiplexer, ADM: wavelength add-drop multiplexer.

Because of the dual bus configuration, each network node is equipped with two sets of transceivers, one for each counter-propagating bus, as shown in Figure 3.1. In normal operation, Bus A and Bus B propagate 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 Figure 3.3. For data reception, each node is assigned with a wavelength channel of a unique wavelength. Data retrieval is achieved by means of an optical demultiplexer, such as AWG or a demultiplexer based on a fiber Bragg grating [29], to select the wavelength assigned to that node for data reception. For data transmission, the node can compete for empty slots on the wavelength channel assigned to the destined node. The detection of slot availability and selection of wavelength channel are controlled by a MAC unit. A slot quota for individual nodes can be set to guarantee network throughput fairness. To facilitate the access of the time slots on each wavelength channel, baseband data packets are transmitted together with a RF pilot tone as an occupancy indicator of that time slot, as shown in Figure 3.4. The RF pilot tone frequency can be identical for all channels. The transmitter may consist of a tunable add-drop multiplexer (ADM), such as an acousto-optic tunable-filter-based ADM [30] or an arrayed-waveguide-grating-based ADM [31], to select the destined wavelength channel from the incoming multiple wavelength channels from the head node, and encode the

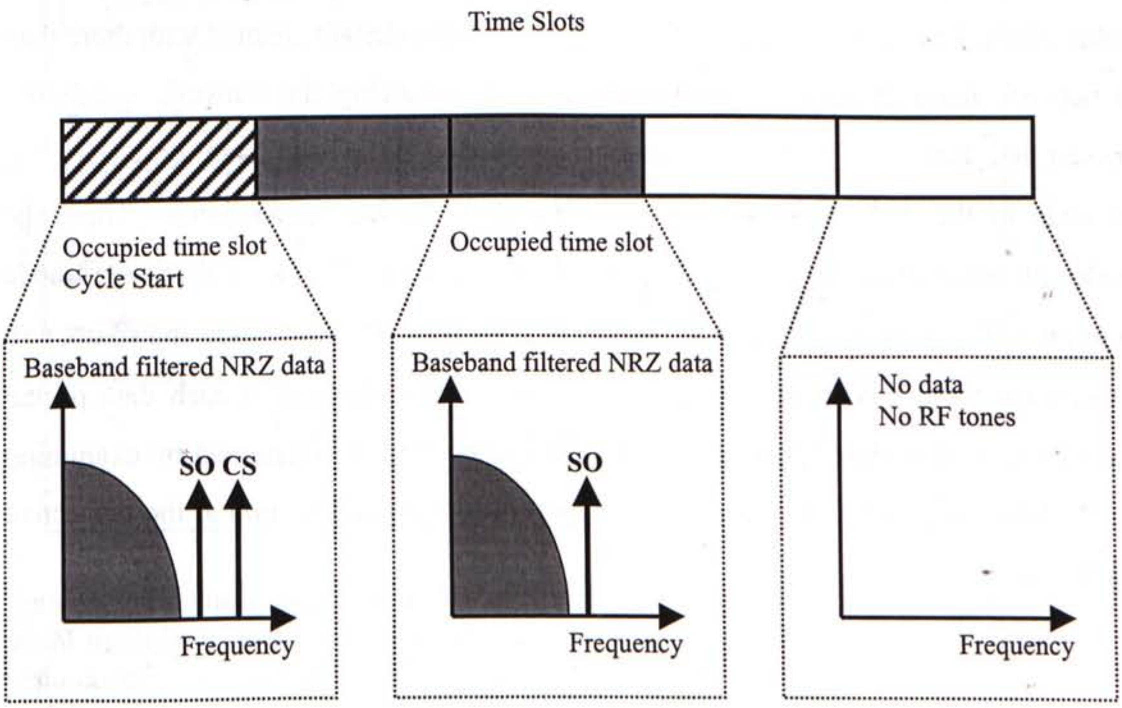


Figure 3.4: Packet access signaling

local data onto it via an optical modulator. The unselected wavelength channels will be passed onto the next node. Once the wavelength channel is selected, the transmitting node first senses the occupancy of the channel by tapping off a small fraction of optical power from the channel. The tapped signals are detected by a photodiode followed by a RF band-pass filter centered at the pilot tone frequency. If the RF pilot tone is detected, the electronic switch at the RF input of the modulator is opened, prohibiting any out-going data packets. If no pilot tone is detected and there are data waiting to be sent, the electronic switch will be closed. The data packets multiplexed with a locally-generated RF pilot tone will modulate the empty slots on the selected wavelength channel through an optical modulator. Note that since the pilot tone frequency is identical for all nodes, all transmitters and pilot tone detection circuits can be identical, thus greatly simplifying the system implementation and cost. Delays introduced by the electronic processing of the RF pilot tone and the modulator are overcome by using a fiber delay line. If the node has nothing to send or it fails, all wavelength channels will be forwarded to the next node without any local processing.

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. Consider that there are N wavelength channels generated at the head node, $\lambda_1,\ldots,\lambda_N$. The first node to the N^{th} node will be receiving at λ_1 to λ_N, respectively. Then, the wavelength assignment will be repeated, therefore 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 constrained in the packet header upon detection at the respective receiving network nodes.

3.3.2 Experimental Results

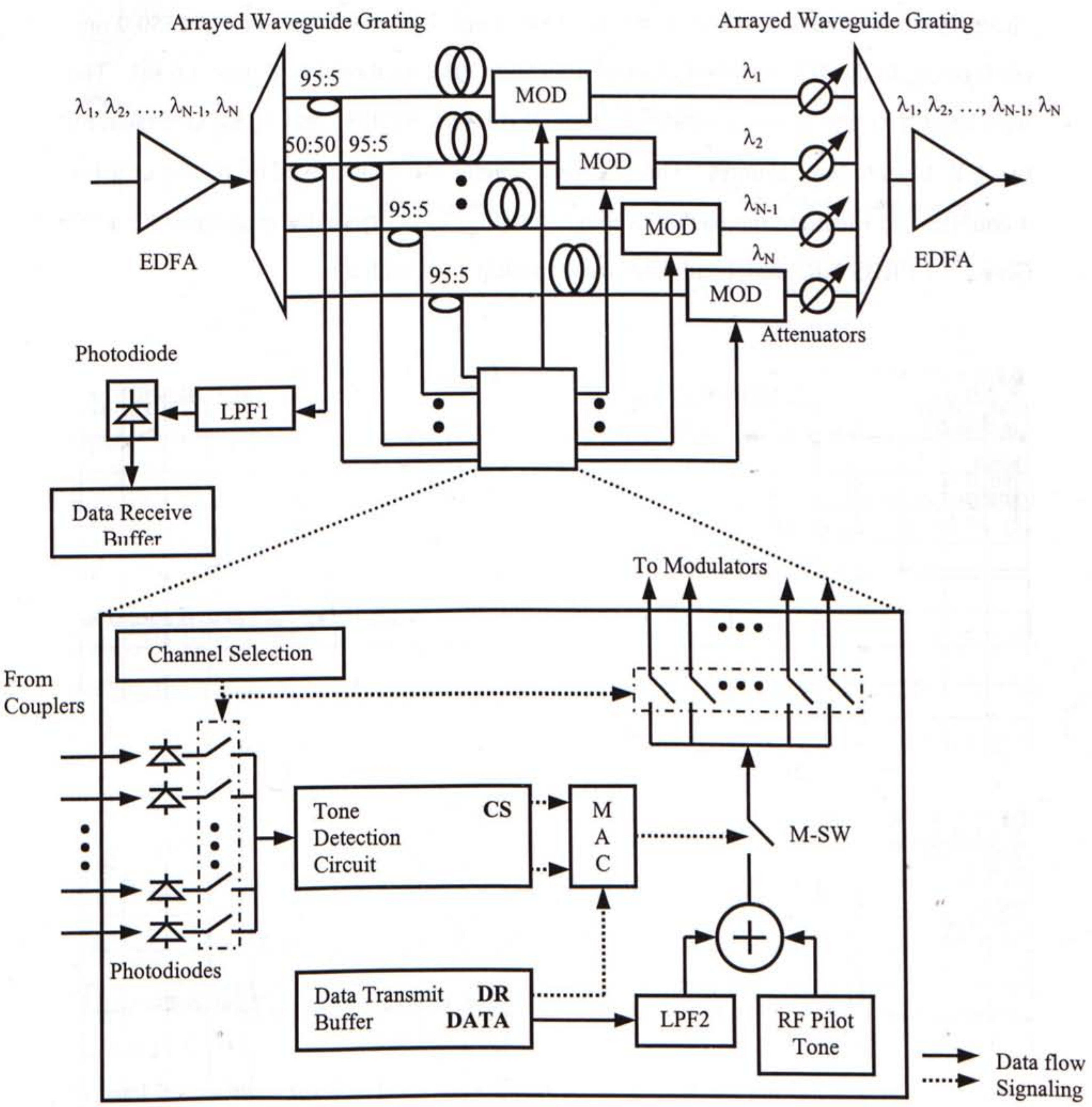


Figure 3.5: Photonic implementation of a network node transceiver on one bus. MOD: optical modulator, EDFA: Erbium-doped fiber amplifier, LPF: RF low-pass filter, MAC: media access control unit, CS: "Cycle-Start" flag, SO: "Slot Occupied" flag, DR: "Data Ready" flag, DATA: data to be sent.

Based on an experimental setup similar to Figure 3.5, we have demonstrated the proposed network with four data channels using a channel spacing of 100-GHz. The four WDM channels are located at λ_1=1548.5 nm, λ_2=1549.3 nm, λ_3=1550.1 nm and λ_4=1550.9 nm, conforming to the ITU standard channel allocation grid, as shown in Figure 3.6 (a). The wavelengths 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. The four wavelengths are multiplexed by means of a 1 × 4 coupler. To illustrate the packet access capability, λ_2 is externally modulated by a 2.3 Gb/s 2^{15}-1 PRBS NRZ baseband data stream multiplexed with a

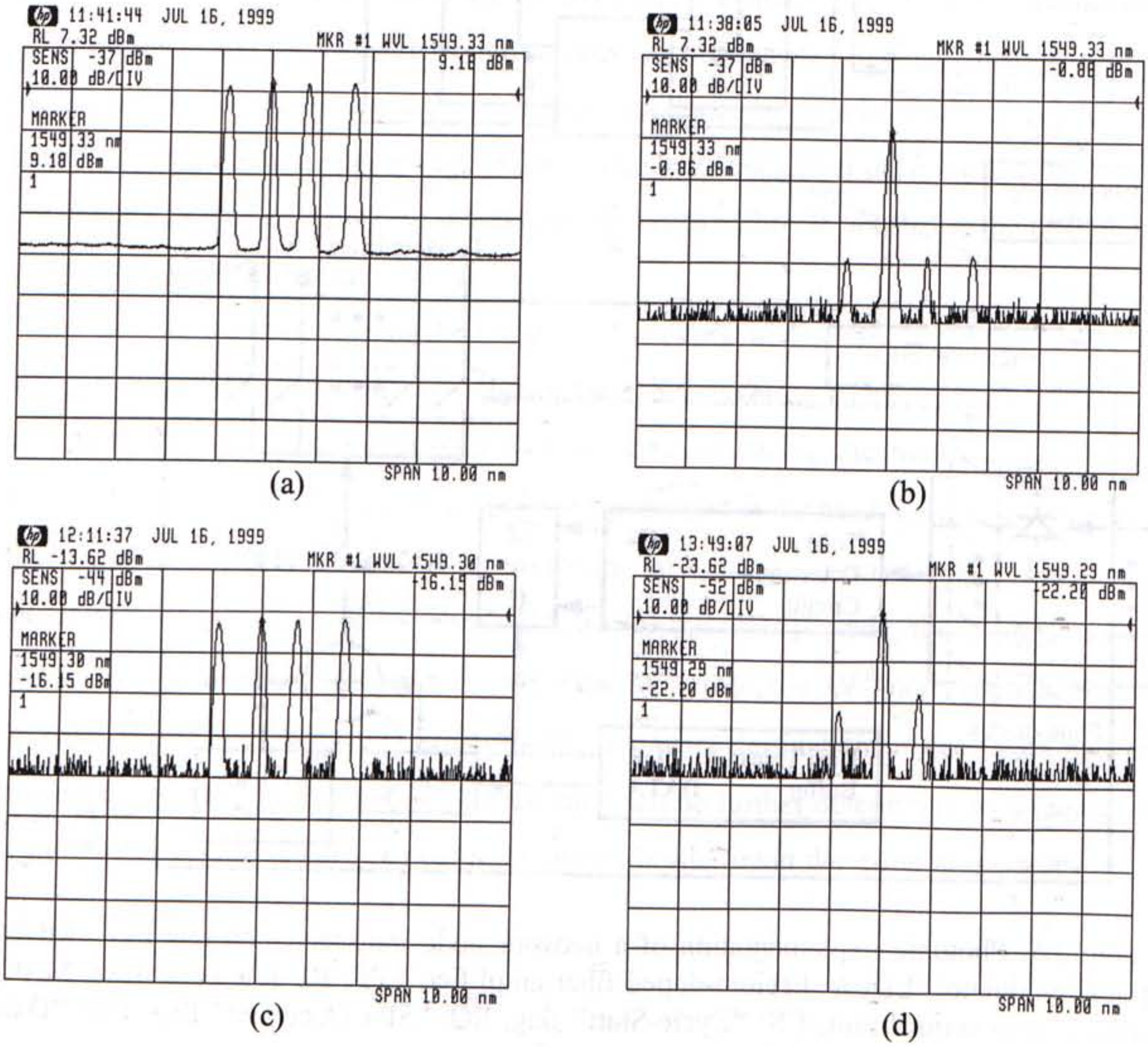
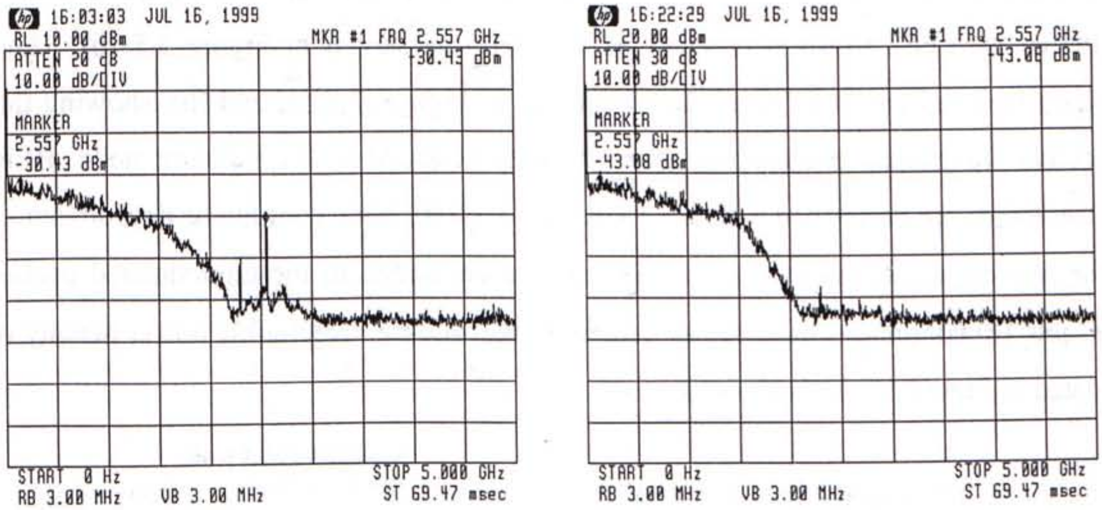


Figure 3.6: Experimental results: Optical spectra at the (a) input to the network node; (b) input of modulator within network node 2 showing the demultiplexed wavelength channel at λ_2; (c) output of network node showing the wavelength channels multiplexed again; (d) input of detector at network node 3 after filtering.



(a) (b)

Figure 3.7: Experimental results: Rf spectra of (a) wavelength channel at λ_2 with slot occupation indicated by the presence of a pilot tone at 2.56 GHz; data is filtered by a low-pass filter (3-dB bandwidth = 2.4 GHz) before being multiplexed with the pilot tone; (b) same wavelength channel measured at the detector but with pilot tone removed by the low-pass filter (3-dB bandwidth = 2.4 GHz).

2.56 GHz RF pilot tone as shown in Figure 3.7 (a). Prior to being fed to the modulator, the baseband signals are chopped by periodic square pulses of 133 μs in length such that λ_2 consists of modulated signals interrupted periodically by slots of unmodulated signals to simulate the input channel to the network node.

Figure 3.6 (b) shows the wavelength selection of λ_2 for transmission by demultiplexing the four wavelengths with the first AWG. To input data to available time slots on λ_2, 5% of the demultiplexed optical signal at λ_2 is fed to the control processing circuitry for RF tone detection, while 95% of the signal is directed to an optical Mach-Zehnder $LiNbO_3$ modulator through a fiber delay line of 100 m. A 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 switches (M-SW) will then be closed for 125 μs for data injection from the local buffer. This is achieved by first low-pass filtering of the baseband NRZ data (LPF2, 3-dB bandwidth 2.4 GHz), followed by combining with a locally generated RF tone and feeding 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 by a second AWG. To examine the data waveform,

λ_2 is demultiplexed and detected. There is little interference from the RF pilot tone as it is filtered by LPF2 (3-dB bandwidth of 2.4 GHz) as shown in Figure 3.7 (b). The resultant received data waveforms are displayed in Figures 3.8 (a) and (b), showing the respective waveforms before, and after, the data is added at the network node. BER measurements are performed with a 2.3 Gb/s 2^{15}-1 PRBS NRZ continuous data stream at λ_2 for two cases: (a) pilot-tone multiplexed data are added to the unmodulated packet slots, and (b) continuous modulation with no packet adding. Negligible power penalty is indicated in Figure 3.9 for both cases.

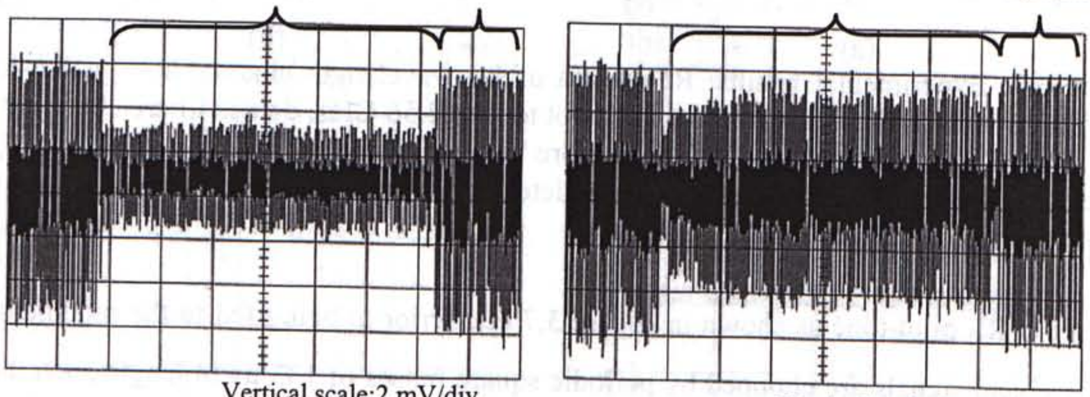


Figure 3.8: Recorded signal waveforms of channel 2 at node 3: (a) before and (b) after data is added at node 2.

Figure 3.10 shows the data transmitter circuit. The 2.56 GHz pilot tone is down-mixed to 10 MHz in the mixer stage and then amplified and filtered for detection. The tone detection circuit compares the incoming frequency to a 10 MHz clock to determine a match. If a mismatch occurs, that means that the pilot tone indicating slot occupancy is not present and the switch (M-SW) will be closed for 125 μs to allow the adding of data into the empty time slot. The total processing time is about 10 μs.

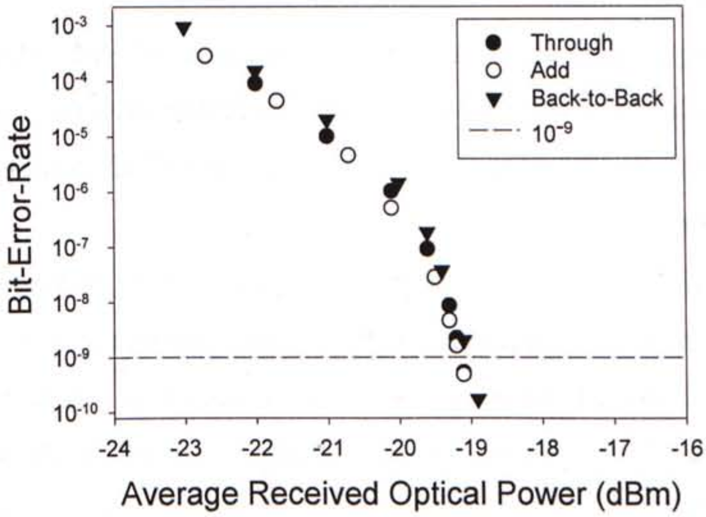


Figure 3.9: BER measurements of the wavelength channel at λ_2 utilizing a 2.3 Gb/s 2^{15}-1 NRZ PRBS: (•) passing through the network node; (○) added to the unmodulated wavelength channel from the network node; and (▾) back-to-back measurement.

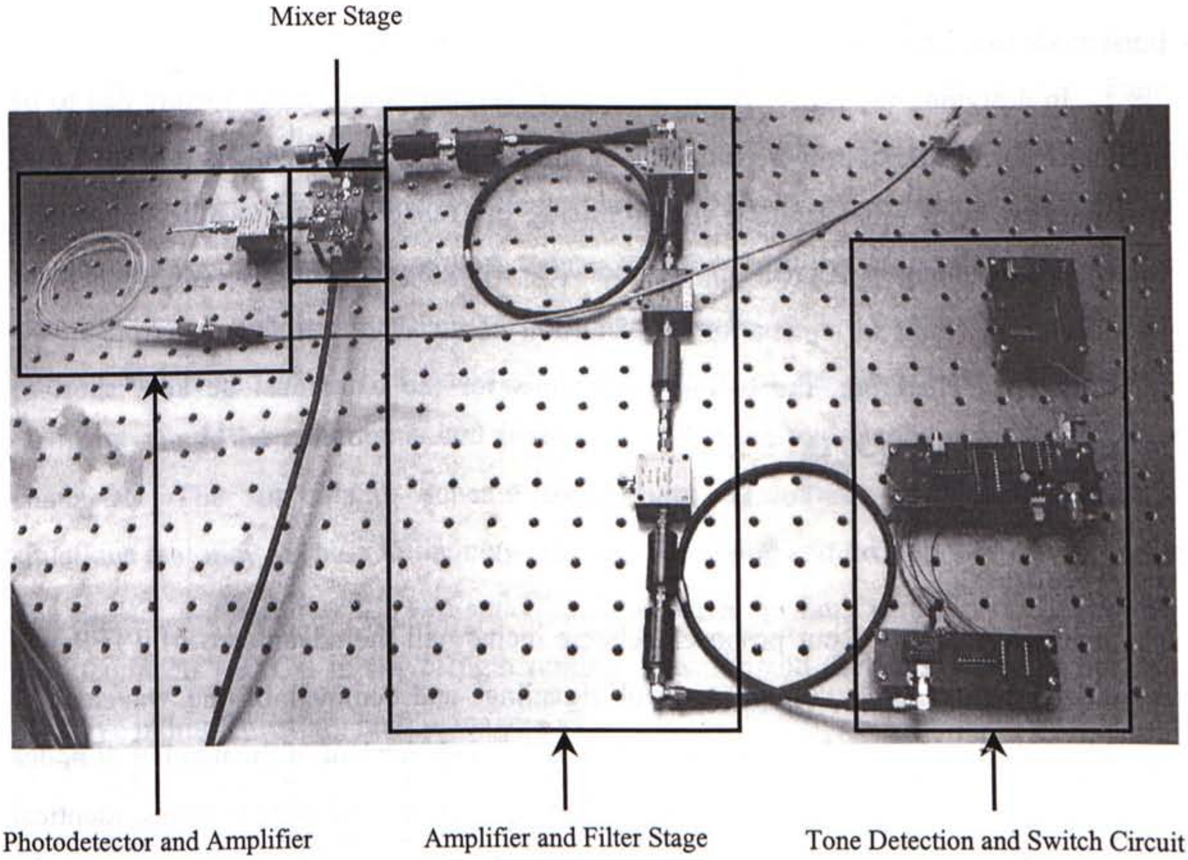


Figure 3.10: Data transmitter circuit. A pilot tone present in a time slot indicates data is present. A missing pilot tone will cause the switch to close, adding data into the empty time slot

3.3.3 Discussion

Because of the limited choice of filters in our possession, the data rate is kept below 2.4 GHz so that the pilot tones could be filtered off before data detection. By obtaining a 2.5 GHz low-pass filter, the data rate could be increased to OC-12, conforming to data rates of existing networks.

The detection time is presently in the range of ~10 μs, but can be reduced. The detection circuit checks for consecutive misses before closing the switch. At present, the checks are only conducted during the half of the clock cycle that is "high". A parallel circuit conducting checks during the "low" half of a clock cycle would reduce the detection time in half.

The bit-error-rate measurements conducted were only for continuous data, either from the first node or from the second node. To properly gauge the packet adding ability of the second node, bit-error-rate measurements should be conducted in burst mode. But burst mode measurements are difficult and require specialized equipment.

In designing the prototype of the data transmitter board, many factors had to be accounted for. Without proper grounding or shielding, signals from one part of the board will interfere with other signals, compromising the reliability of the detection board. Impedance matching is of great importance when using high data rates. Any impedance mismatch will result in attenuation or distortion of the data, introducing errors in the transmission. Therefore, the board connections for the data must be kept short or impedance matched to 50 Ω.

3.3.4 Summary

The main advantages of our proposed scheme include all the advantages of TTFR and centralized light sources, simple control signaling, and removal of the wavelength-matching problem. Thus the hardware complexity is independent of the number of nodes in the network. Because the same pilot tone frequency is used for all nodes, identical transceiver hardware can be implemented for all nodes, which greatly reduces the implementation complexity and cost. With our simple photonic implementation, together with our ACTA protocol, a highly efficient wavelength-division TCMA network can be achieved.

Chapter 4

Fault Surveillance for Optical Cross-Connects in Wavelength Routing Networks

In a WDM network a number of components may fail or degrade in performance. Fault surveillance schemes have been suggested for most of the components, such as the optical fiber links, EDFAs, and wavelength routers. The schemes help to facilitate the fault management function of network management by detecting and reporting any faults immediately so that appropriate steps can be made to keep network downtime, data retransmission and loss, to a minimum. Monitoring of the fiber links and network elements should be continuous and performed in-service without interrupting the data channels. The surveillance scheme should also encompass all possible dynamic situations that may develop in the network, such as adding and dropping of channels. In this chapter, we will describe two surveillance schemes for fault identification of optical cross-connects (OXCs) in wavelength routing networks and they are shown to be very effective in implementing fault management.

This chapter is organized as follows. Section 4.1 describes the basic architecture of wavelength routing networks. Section 4.2 discusses other fault surveillance schemes proposed for optical networks. Section 4.3 presents the principles and experimental results of our proposed surveillance schemes for OXCs in wavelength routing networks.

4.1 Wavelength Routing Networks

In order to have a wavelength routing network [32, 33], we need appropriate routing devices to interconnect multiple point-to-point WDM links. These wavelength routers can be grouped into two broad categories: passive router, and optical cross-connect (OXC). The routing in these devices is all performed optically, so that no opto-electrical conversion is required. Optical amplifiers can be added on the WDM links to increase the network span by compensating for attenuation and splitting losses.

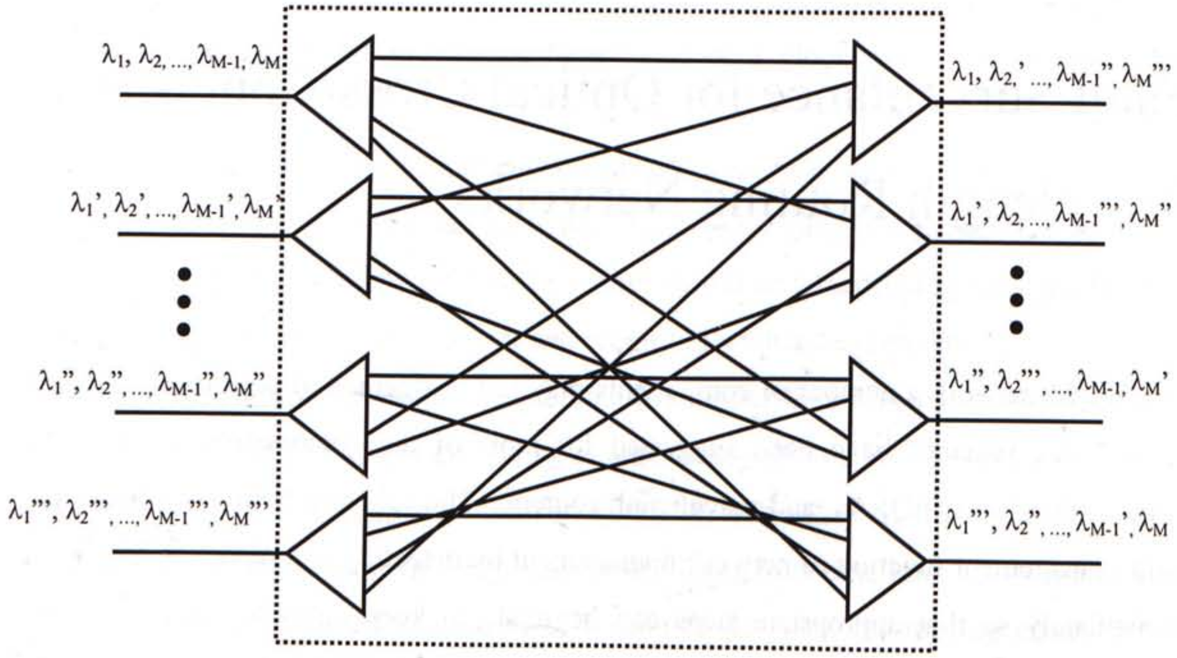


Figure 4.1: A passive router

A passive router can separately route each of several wavelengths that are incident on an input fiber to separate output fibers. This device allows wavelength reuse. The wavelength on which an input port gets routed to an output port depends on a routing matrix characterizing the router; this matrix is determined by the internal connections between the demultiplexing and multiplexing stages inside the router. The routing matrix is fixed and cannot be changed. Such routers are commercially available, and are also known as waveguide grating routers (WGRs). Assuming there are as many wavelengths as there are fiber ports, a passive router with N input and N output ports can route N^2 simultaneous connections through itself.

The OXC, like a passive router, also allows wavelength reuse and supports N^2 simultaneous connections. But the OXC has a further enhancement over the passive router in that its routing matrix can be reconfigured on demand using internal switches. Because the OXC requires power and has active components, it is not as fault-tolerant as the passive router, which doesn't need to be powered. The OXC is also referred to as an active switch, wavelength-routing switch (WRS), or wavelength selective cross-connect (WSXC). The OXC can be enhanced with an additional capability by converting to another wavelength just before it enters the multiplexing stage before the output fiber. An OXC equipped with such a wavelength-conversion facility is more capable, and it is referred to as a wavelength interchanging cross-connect (WIXC).

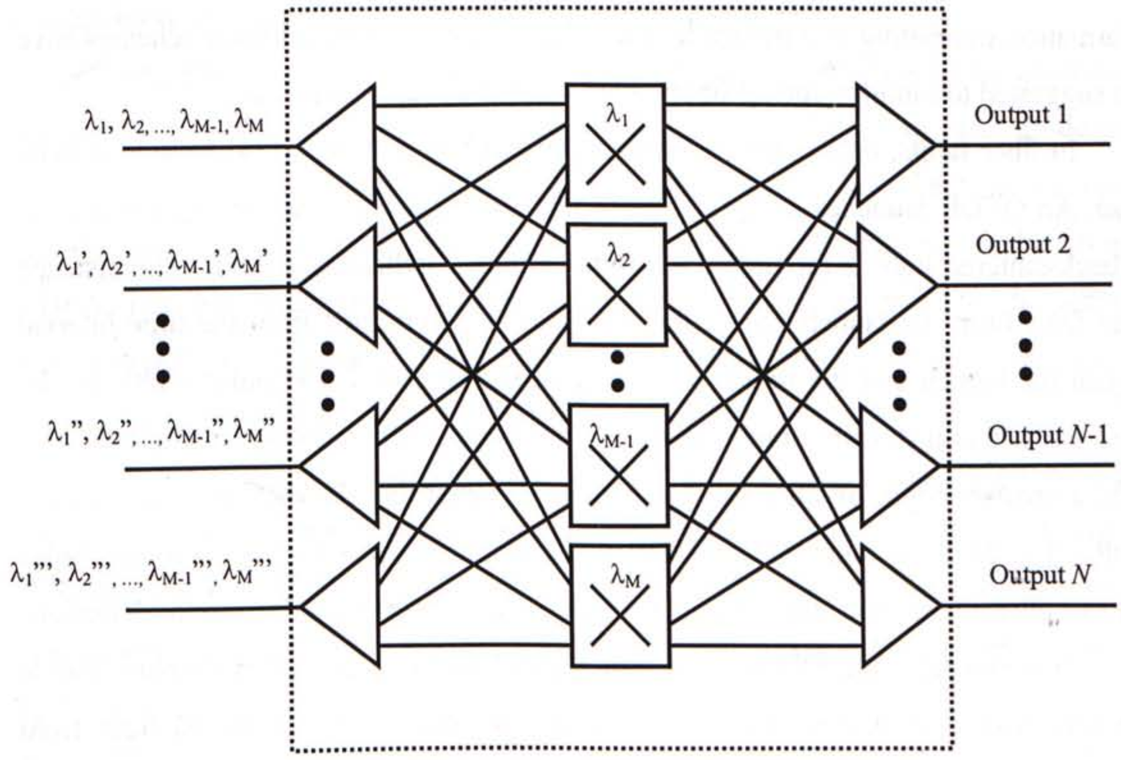


Figure 4.2: Optical cross-connect.

The OXC has N incoming fibers and N outgoing fibers. On each incoming fiber there are M wavelength channels. The wavelengths on each incoming fiber are separated using a grating demultiplexer. The outputs of the demultiplexers are directed to an array of M $N \times N$ optical switches between the demultiplexer and the multiplexer stages. All signals of a given wavelength are then directed to the same switch. The switched signals are then directed to multiplexers that are associated with the output ports, where multiple wavelength channels are multiplexed before launching them onto an output fiber. The all-optical wavelength-dependent routing process continues for multiple router nodes before reaching the destination end node. Thus the connection between the end nodes can be setup and the routing paths are transparent to the users. Besides, the signal dedicated to a specific end node will not be split to other irrelevant destinations. Thus a better power budget is obtained and a longer network span is allowed.

4.2 Options in Fault Surveillance

In a WDM network a number of components in the optical-path may fail or degrade in performance, translating into tremendous data loss. Numerous surveillance schemes have been suggested to monitor optical fibers, EDFAs, and wavelength routers.

In fiber faults, optical time domain reflectometers (OTDRs) [34] have long been in use. An OTDR launches an optical pulse into a fiber using a dedicated laser source, and backscattered light is monitored for abrupt changes indicating a fault. The distance of the fault from the launch end of the fiber can be determined from the time interval between the launch and the return of the backscattered peak. The pulse width can be varied for different dynamic range or resolution requirements. By increasing the pulse width, a greater length of fiber can be monitored, increasing the dynamic range of the OTDR. The dynamic range of an OTDR is the amount of loss that the launched pulse can incur after a fault, and still generate enough backscattering or reflection for detection.

Unfortunately, the OTDR runs into a problem in systems that employ optical amplifiers with optical isolators. The isolators prevent the backscattered light from returning to the OTDR for detection. Therefore, revised OTDR techniques have been suggested to overcome this problem. One solution suggests modification of EDFAs, incorporating optical circulators to provide a reverse path for the backscattered OTDR signal [35]. Another scheme suggests the same modifications to the EDFAs, but uses Brillouin amplification [36]. The forward line signal amplifies a backward supervisory signal through stimulated Brillouin scattering in the transmission fiber. At the amplifier, the supervisory signal is terminated and regenerated on the other side. Another approach is to use coherent OTDR techniques [37], which would not require the EDFA modification. However, it has been observed that the use of strong monitoring signals in some OTDR techniques may deplete the gain and induce transient gain compression in the optical amplifier [38]. The onset of nonlinear effects due to these intense monitoring signals has also been reported [39]. These undesirable effects impose a severe system penalty.

One Non-OTDR technique that is an attractive alternative, utilizes unused residual ASE noise from EDFAs as the source for all monitoring channels [40], therefore requiring no additional light sources. After each EDFA is placed a fiber Bragg grating (FBG) with a distinct center wavelength located in the ASE spectrum away from the wavelengths carrying data. Another technique uses an in-line anisotropic optical phase modulator to modulate the polarization state of the data wavelength.

Any EDFA failures will severely degrade the data channels, so it is imperative to monitor their performance. One approach is to modulate the pump laser diode or the ASE with a low frequency signal [41]. This modulation will, however, impose a power penalty on the data channels. Other approaches are the aforementioned re-design of the EDFA, incorporating optical circulators to provide a reverse path for the amplified backscattered OTDR signal, and the utilization of unused residual ASE noise as the light source for monitoring channels in conjunction with FBGs.

The wavelength router, whether a fiber grating router or arrayed waveguide grating (AWG), can degrade in performance due to temperature changes or aging [42]. This can cause a misalignment between their transmission wavelengths and the data wavelengths that will lead to a power loss. One approach is to tune the laser wavelengths to realign them with the wavelength router channels. One proposed method is based on the fact that the temperature coefficient of an FBG is close to that of an AWG [42]. The alignment of a monitor wavelength with the FBG will realign the data channels with those of the AWG. Another technique involves continually tuning the laser to minimize power loss [43] through the router.

Another approach is to change the temperature of the wavelength router to realign the router wavelengths with the data wavelengths. One scheme requires equalizing the monitoring wavelength's power at the outputs of two adjacent router channels [44].

Another similar scheme makes its adjustments while monitoring multiple wavelengths by using the same crossover property in an AWG [45].

Also of concern is that the data wavelengths maybe improperly routed by the wavelength router. Therefore it is desirable to monitor the routing of data wavelengths. One method is to tag each data wavelength with a low frequency subcarrier signal by amplitude modulation [46, 47]. The subcarrier can be encoded with routing information for the data wavelength, containing its origin node, destination node, and designated path. Also, the power detected in the subcarrier will provide power level information on the data signal. This subcarrier information can easily be read using taps and low speed detectors at various points throughout the network to ensure proper routing.

4.3 Optical Path Surveillance of Optical Cross-Connects in Wavelength Routing Networks

The OXC [48] is one of the most critical enabling technologies that, together with other network elements, offer scalability, high throughput, and multi-access capability in all-optical wavelength routing networks. Through the OXCs, wavelength channels from various sources are routed to their respective destinations according to prescribed switch settings registered in a routing control module located at these devices. These settings help to define the optical paths for different wavelength channels and will be renewed by the network configuration management prior to each data transmission.

While the transmission of the signaling control is tightly controlled and corruption in the messages is highly unlikely, a failure or malfunction in the optical switches in OXCs [49, 50] will route streams of data to the wrong destinations. Network performance will suffer substantially as the data is either lost or exposed to other users. It is therefore of immense interest to develop a surveillance scheme at each OXC such that any routing failure can be detected at the earliest possible stage so that appropriate actions can be taken to remedy it.

Optical path management schemes based on a pilot tone [49] and a supervisory channel [51] were previously proposed, but these schemes sacrificed data transparency and privacy, and thus are intrusive in nature. We propose two novel non-intrusive surveillance schemes for monitoring the wavelength routing status at OXCs.

For the first scheme [52], the basic principle of operation is to assign each input fiber of the OXC with a unique identification (ID) in optical form, which will be detected and processed immediately at each output port without tapping off any power at the data wavelengths. Thus any failure or incorrect physical connection at the switches can be detected at once by comparing the detected physical connection and the switch-setting information stored in the routing control module. Such information will be forwarded to the central office at once to report the failure. This not only facilitates fault identification, but also informs the network configuration management such that network downtime, data retransmission and loss can be kept at a minimum. Here, my contributions include conceiving of the surveillance scheme and implementing it. Also, I wrote the paper for publication, obtaining the measurements needed in the process.

The second approach to wavelength-routing monitoring in OXCs involves the addition of frequency tones onto wavelength channels as channel identification (ID) [53]. The supervisory function can be incorporated in the OXC design such that optical-path routing can always be monitored. Use of pilot tones in supervisory system was discussed previously [46, 47, 49, 51] and the tones were added at the headend along with the modulated data for signal power and system status monitoring. In [47], use of RF pilot tones to supervise individual wavelength channels along their optical paths was proposed, and crosstalk among pilot tones in Erbium doped fiber amplifier (EDFA) was also measured. Our proposed scheme is a variation of [47], and experiments were demonstrated on an arrayed waveguide grating (AWG) in a loopback configuration to simulate the cascade of two OXCs. The system is also analyzed to determine the pilot tone removal requirement by EDFAs. While using pilot tones is not new, tone removal using EDFAs is a new concept conceived and implemented by myself. Obtaining measurements and writing of the paper submitted for publication were other tasks that I performed in realizing this scheme. Other pilot tone removal schemes have used semiconductor optical amplifiers (SOA) [54], an integrated semiconductor optical amplifier/distributed feedback laser (SOA/DFB) [55], and a fiber acousto-optic attenuator (FAOA) [56]. In [54], the pilot tone headers are stripped from the data by switching the

SOA "off" during header detection. As for [55], the pilot tone is only added when the data is "high", and is removed by saturation as the "high" is converted to the output "low" level in the SOA/DFB. In [56], the pilot tone is suppressed by using the FAOA and a feed-forward control circuit to variably attenuate the power level of each channel accordingly.

4.3.1 Scanning Amplified Spontaneous Emission Identification Surveillance Scheme

Proposed Surveillance Scheme for OXC

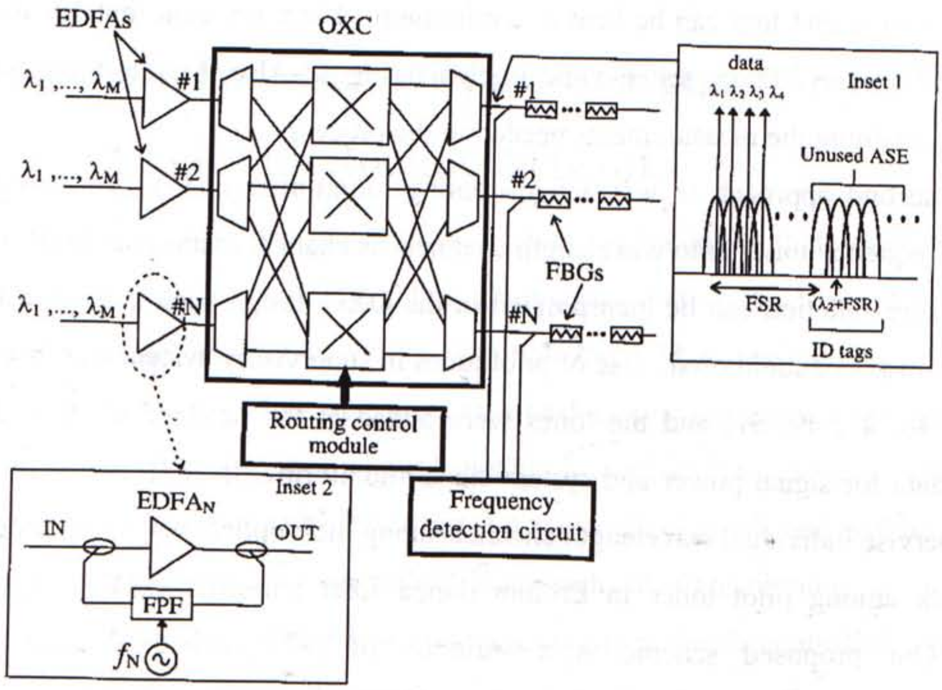


Figure 4.3: Proposed surveillance scheme for optical cross-connect

Figure 4.3 shows the proposed surveillance scheme for an $N \times N$ OXC, which can be formed by a total of $2N$ (N incoming and N outgoing) $1 \times M$ arrayed waveguide gratings (AWG) interconnected by M banks of NxN optical space switches, assuming that there are M data wavelengths (λ_1, ..., λ_M) carried on each input fiber. Identical wavelength channels but from different input fibers will be routed by the same $N \times N$ optical switch to various output fibers in accordance to the routing assignment kept in the routing control module. We assume that there is an Erbium-doped fiber amplifier (EDFA) at each input port of the OXC for gain equalization [57] and loss compensation. The free spectral range (FSR_{AWG}) of the AWG is chosen to be less than one-half of the usable gain spectrum of the EDFA. Because of the periodicity property of the AWG, there exists both routed wavelength channels and filtered amplified spontaneous emission (ASE) located at one FSR_{AWG} from the corresponding routed wavelength channels at the output ports.

A unique and distinct ID will be introduced to each input fiber. To generate the ID tag for the i-th input port ($i=1,...,N$), a small portion of the ASE is looped back to the input of $EDFA_i$ through a scanning Fabry-Perot filter (FPF) modulated at a distinct sinusoidal frequency f_i (~kHz) (see Fig. 4.3 inset 1). The scanning period ($1/f_i$) should be chosen to be much less than the gain recovery time (~ms) of the EDFA [58]. The loopback configuration generates lasing action and the amplifier gain is clamped [59]. The selected scanning spectral range of the FPF should cover the unused part of the EDFA, that is, from (λ_1+FSR_{AWG}) to (λ_M+FSR_{AWG}). Accordingly, for a wavelength channel at λ_k being routed by the OXC from the i-th input fiber to the j-th output fiber, there appears an ID tag on the j-th output fiber, located at one FSR_{AWG} from λ_k (i.e. $\lambda_{ID-k}=\lambda_k+FSR_{AWG}$; $k=1,...,M$) and represented by periodic power fluctuation at λ_{ID-k} with an frequency of f_i. Such power fluctuation at λ_{ID-k} is due to the periodic scanning lasing at the i-th input port. Thus, there will be M ID tags on each output fiber, each signifying the input fiber in which the corresponding channel is routed from. However, the IDs for different wavelength channels will not be mixed up because no two channels of identical wavelengths will be routed to the same output port.

On each output fiber, fiber Bragg gratings (FBG) with center wavelengths at $\lambda_{FBG}=\lambda_{ID-k}$ ($=\lambda_k+FSR_{AWG}$; $k=1,...,M$) are used to drop the ID tags through circulators. The ID tags will be demultiplexed and detected by photodiodes [60]. A frequency detection circuit is then used to recover the frequency of the power fluctuation at each ID tag. For instance, a recovered frequency f_r of the power fluctuation at λ_{ID-k} indicates that the wavelength channel λ_k has been routed from the r-th input fiber. In this way, the physical OXC connection can be obtained. By comparing this as-detected physical connection with the prescribed switch settings stored in the routing control module, any failure or error in routing can immediately be identified. Finally, a broadband rejection filter is to be placed after all the FBGs on each output fiber to eliminate the IDs, and new IDs will be generated at the input ports of the next OXC.

Experimental Results

In our experiment, a thermally stabilized 16x16 AWG with a channel spacing of 100 GHz, an FSR_{AWG} of 12.8 nm and a 3-dB full-width of 0.4 nm in a loopback configuration is used to simulate the OXC. Two EDFAs ($EDFA_1$ and $EDFA_3$) with similar gain outputs are placed at the input ports 1 and 3 of the AWG, respectively. Output ports 4 and 6, which correspond to the routing of two different data channels but of identical wavelength at λ=1546.7 nm from input ports 1 and 3, are looped back to input port 2 through a 2x1 optical switch (insertion loss = 0.3 dB and switching time = ~300 ms). The resultant configuration can route the data channel λ, either from input port 1 or 3 to output port 5, depending on the state of the 2x1 optical switch. This also generates three neighboring IDs at output port 5, two originating from one input EDFA and one from the other, thus the ID at λ_{ID} to be detected is under the influence of the neighboring ID tags and forms the worst-case scenario. An FBG with a center wavelength of $\lambda_{FBG}=\lambda_{ID}$=1559.5 nm (one FSR_{AWG} away from λ) and a 3-dB full-width of 1 nm is placed at the output port 5 for reflecting the power at λ_{ID} (ID).

To generate the channel ID, a small portion from each of the amplifiers' outputs (through a 95:5 coupler) is fed back to its input (through a 50:50 coupler). A tunable FPF of finesse 100 with a 3-dB bandwidth of 0.7 nm is placed in between the couplers at each input fiber 1 and 3. By applying a sinusoidal voltage of 0.4 V (peak-to-peak) at 10 kHz to the FFP at input port 1 and at 12 kHz to input port 3, we thus obtain laser emissions scanning at the corresponding rates and form the IDs for the input ports 1 and 3, respectively.

A simple detection circuit is implemented after the photodiode and is used to recover the fluctuation frequency of the power reflected from the FBG, which is the ID for the data channel. Figure 4.4 shows the recovered waveforms of the detected ID when the 2x1 switch is in two different states. The frequency of the pulse pattern changes from 10 kHz to 12 kHz when the 2x1 switch's input is changed from output port 4 to 6, and vice versa. This shows our scheme can effectively detect the routing status of the OXC.

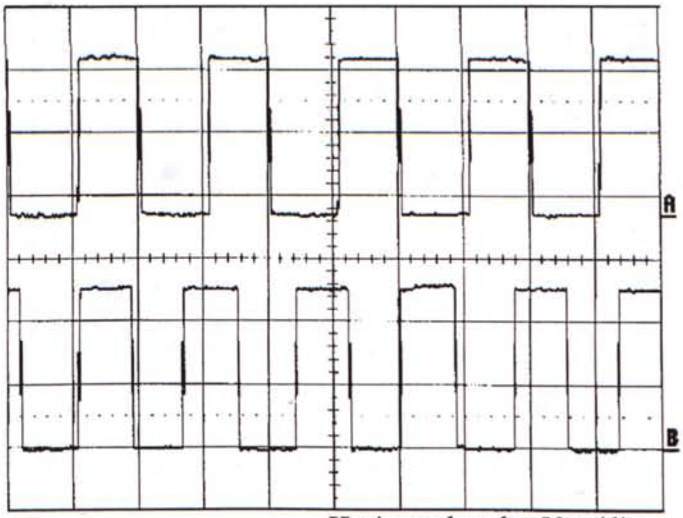


Figure 4.4: Recovered waveform of the optical power reflected from FBG when the 2x1 switch's input is connected to OXC's output fiber (upper trace) #6, and (lower trace) #4 with f_1 = 10 kHz and f_3=12 kHz. (Horizontal scale: 50μs/div)

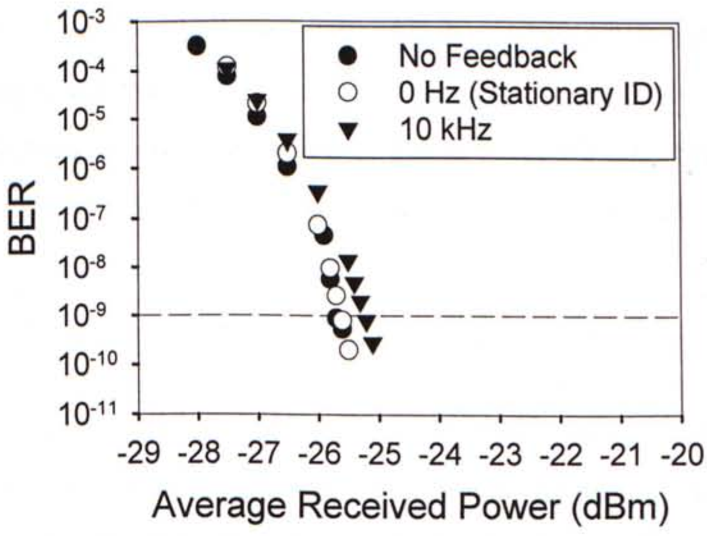


Figure 4.5: BER performance of the data channel with and without the proposed supervisory scheme. The data channel is externally modulated by a 1-Gb/s 2^{15}-1 NRZ PRBS and the channel ID is set at 10 kHz.

BER measurements were also performed for the data channel on λ, where the channel is externally modulated by a 1-Gb/s 2^{15}-1 PRBS NRZ data stream, for the cases: (1) stationary channel ID, and (2) channel ID scanning at 10 kHz. The results are displayed in Figure 4.5, showing there is only 0.2 dB power penalty resulting from the scanning channel ID.

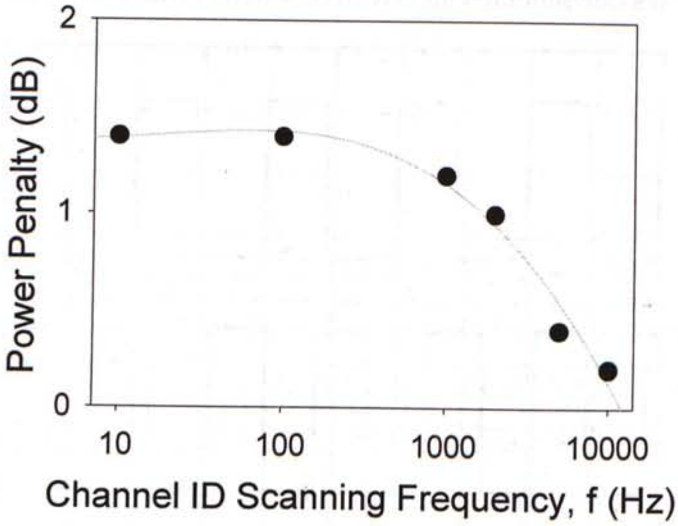


Figure 4.6: Power penalty of the data channel (externally modulated by a 1-Gb/s 2^{15}-1 PRBS NRZ stream) for the channel ID scanning at different frequencies *f*.

BER measurements were also performed for the data channel on λ, for channel ID scanning at different frequencies, *f*. The corresponding system penalties are displayed in Figure 4.6, showing that the penalty drops below 1 dB when *f* is greater than 1.2 kHz. This result agrees with the fact that the scanning period of the channel ID should be kept much less than the gain recovery time of the EDFA in order to have negligible transient effect induced to the data channels due to the periodic scanning.

Discussion

Some characteristics of the electronically-tunable Fabry-Perot filter have to be taken into account when implementing this scheme. There is a stated frequency limit to how fast the filter can be scanned. But even at frequencies below this limit the response of the filter can be frequency dependent. Some wavelengths at the edges that are covered at lower frequencies are not covered when higher frequencies are used. To ensure the integrity of this scheme, it is important to check beforehand that all the desired wavelengths are scanned for the selected ID frequencies.

Another property of the filter that requires attention is the hysteresis during scanning. For the same applied voltage a different wavelength can be obtained depending on whether the voltage is scanning up or down. It has been observed that a slight shift may occur in the range of wavelengths covered. Prolonged observation in advance will show whether the desired wavelengths are always scanned.

The flatness of EDFA gain profile in the region used for wavelength scanning governs how well this scheme gain clamps the data wavelengths. If there is any slope, the gain for each wavelength scanned will be different, resulting in a gain fluctuation in the wavelengths possessing data.

The coupler ratios for EDFA feedback to generate the scanning source require some optimizing. We want to amplify the data channels as much as possible but also generate a surveillance source that is easily detectable. Increasing the coupling ratios for the feedback branch will reduce the gain for the data channels but increase the power of the surveillance source. On the other hand, reducing the coupling ratios for feedback will increase the gain to the data channels but will also make surveillance source more difficult to detect as its power is reduced.

Summary

In this section we have proposed and demonstrated a novel and real-time routing surveillance scheme at the OXCs in an all-optical network. It should be noted that the scheme involves only the detection and verification of the ID tags. No power tapping of the data wavelength or a dedicated monitoring light source is required, so data privacy is assured. It can facilitate the network management in the optical layer of all-optical and reconfigurable transport networks.

4.3.2 Pilot-tone Based Surveillance and Removal Scheme

Principle of Operation

The principle of operation is based on adding an individual frequency tone functioning as the channel ID to all incoming wavelength channels in each of the *N* fibers entering the OXC. The channel IDs are then processed at the output ports and cross-referencing with the control data stored in the routing module will detect errors in channel routing and add-drop. The detected error information will then be forwarded to the central office for immediate remedy.

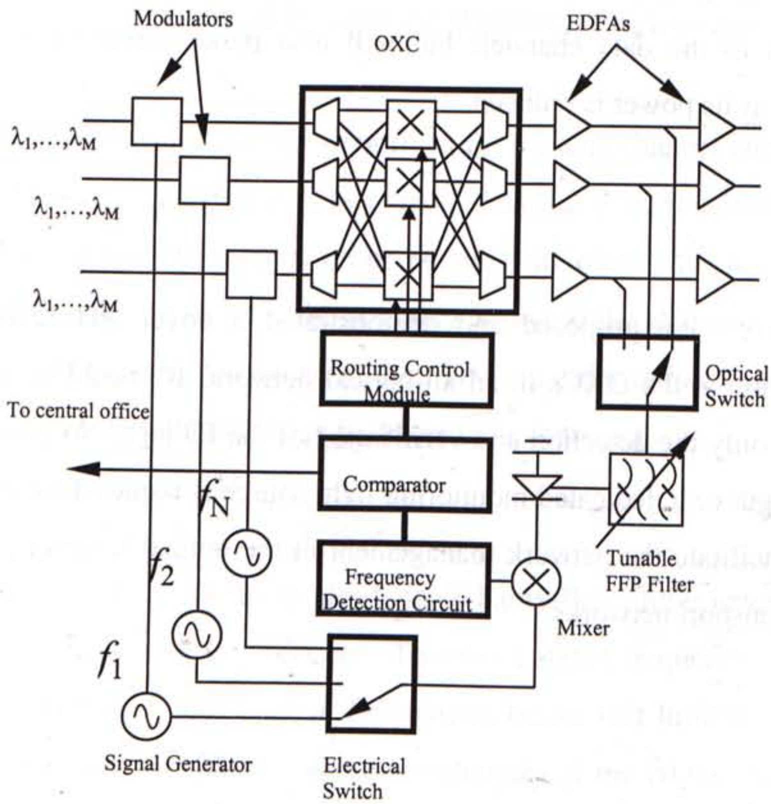


Figure 4.7: Proposed optical-path supervisory scheme for optical cross-connects.

Figure 4.7 shows the proposed optical-path supervisory scheme. The $N \times N$ OXC can be formed by a total of $2N$ (N incoming and N outgoing) $1 \times M$ AWGs interconnected by M banks of $N \times N$ optical space switches, assuming that there are M data wavelengths, $\lambda_1, ..., \lambda_M$, carried on each input fiber. Wavelength channels from different input fibers will be routed by the optical-switches to various output fibers in accordance to the routing assignment.

The channel ID is formed by superimposing a pilot tone of frequency f_i on all wavelength channels carried by fiber i. To achieve this, we require an optical modulator to be inserted in each of the N input ports. On the output side, the channel ID on each wavelength channel is detected by a tunable optical receiver consisting of a scanning Fabry-Perot filter (FPF), a photodiode followed by low-pass filter and frequency detection circuit. To minimize the number of active components, a small fraction of the optical signals is extracted by a tap from each output fiber and connected to the tunable optical receiver via an $N \times 1$ optical switch as shown. Since the routing configuration is usually set for a long duration, mechanical or thermal optical switch of ~ms switching time is adequate for the purpose. Each output fiber is selected in turn, and wavelength channels in each fiber will then be selected by the scanning FPF individually. By comparing the detected physical connections with the switch settings stored in the routing control module, any failure or error in routing can immediately be detected. Finally, EDFAs are placed at the output port to eliminate the channel ID through gain saturation, so that a new channel ID can be added at the input port in the next OXC. The optical amplifiers can also be used as power boosters and equalizers.

Our supervisory scheme is limited by the lifetime and gain characteristics of the EDFA. First, channel IDs cannot be completely eliminated by gain saturation. Accumulated residual amplitudes from previous OXCs can be comparable with that of the current ID, essentially limiting the number of OXCs and thus the size of the network the scheme can support. Second, the temporal response of the EDFA restricts all channel IDs to be between 10 - 100 Hz [47], thereby restricting the usable range of frequencies or the number of IDs that can be used in each OXC. Frequencies in the order of ~Hz are not practical because of long processing time, while high frequencies over kHz are transparent to the EDFA and cannot be eliminated through gain saturation. The limited frequency range can be resolved by frequency reuse, provided all previous channel IDs can effectively be removed from the previous OXCs.

Performance Analysis

The amplitudes of residual channel IDs can be estimated based on the modulation index imposed on the wavelength channels. Without loss of generality, the two EDFAs following the OXC in Fig. 1 can be lumped together as one amplifier. The signal combined with the channel ID is given by

$$\frac{1}{2}[P_o + P_1 d_1(t)]\cdot[1 + m\cdot\sin(2\pi f_1 t + \phi_1)] \tag{4.1}$$

where $[P_o + P_1 d_1(t)]$ describes the ON-OFF modulation of the input data, and f_1 is the frequency of the channel ID, and m ($m << 1$) is the optical modulation index. Through gain saturation, the sinusoidal modulation of the channel ID will be reduced by a factor of r ($r << 1$) by the optical amplifier, which is defined as the ratio of the output optical modulation index to the input optical modulation index. Traversing N stages of OXC, the total modulation can approximately be written as

$$\frac{1}{2}[P_o + P_1 d_1(t)]\cdot[1 + m\cdot\sin(2\pi f_N t + \phi_N) + m\cdot\sum_{j=2}^{N} r^{j-1}\cdot\sin(2\pi f_{j-1} t + \phi_{j-1})] \tag{4.2}$$

where the first and the second sinusoidal terms describing the modulation of the current and the sum of previous IDs, respectively, and f_i and ϕ_i are the corresponding frequencies and phases of ID tones. Because of the small modulation index m, we have dropped all terms describing beatings, which contain multiple orders of m.

There exist two scenarios in which errors can occur in ID detection, when setting the decision threshold at $m/2$ and assuming the worst-case situation where the frequencies and the phases of the previous channel IDs are identical. First, the amplitude of all accumulated previous IDs of frequency f_k is larger than that of the current ID of frequency f_i ($f_i \neq f_k$), corresponding to $m\sum_{j=2}^{N} r^{j-1} > m/2$. Second, the amplitude of the current ID of frequency f_i is cancelled by the accumulated IDs of the same frequency but with phase difference of π, $m - m\sum_{j=2}^{N} r^{j-1} < m/2$. For both cases the expression simplifies to

$$\frac{r - r^N}{1 - r} < \frac{1}{2} \tag{4.3}$$

which gives r <1/3 for large N. Therefore, as long as r is smaller than 1/3, our path-supervisory scheme can be applied with an infinite number of cascaded OXCs. As r is frequency dependent, the r<1/3 requirement will set the limit of the highest frequency tone that can be used for the supervisory scheme.

Experimental Results

Our experimental setup consisting of a thermally stabilized 16 × 16 AWG with a channel spacing of 100 GHz, a free spectral range of 12.8 nm and a 3-dB full-width of 0.4 nm to simulate an OXC. An intensity-modulated optical data channel (1 Gb/s, 2^{15}-1 NRZ PRBS) at λ=1546.7 nm is imposed with a channel ID via a Mach-Zehnder modulator with a cosine wave of f_1 =100 Hz before feeding into input port #1 of the AWG. Two EDFAs each with a 17-dB gain are placed at port #6 which is the output port of the data channel. The first EDFA acts as a limiting amplifier for the second, saturating all incoming channels such that the channel ID in each routed wavelength channel is much reduced. In our experiment, a 5% tap is used to connect each output port to a photoreceiver through an 8 × 1 optical switch (coupling loss of 0.3 dB, switching time of 300 ms) followed by a scanning Fabry-Perot filter as shown. In order to simulate the cascade of two OXCs, the output port #6 is looped back to input port #2 but with a new channel ID of f_2 =90 Hz. The results are shown in Figure 4.8, showing the frequency spectra of the channel IDs (f_1 =100 Hz, f_2 =90 Hz) with data signal. As shown in the inset, the detected power at f_2 was at least 7 dB stronger than that at f_1, showing that the current ID can easily be distinguished from the previous ID.

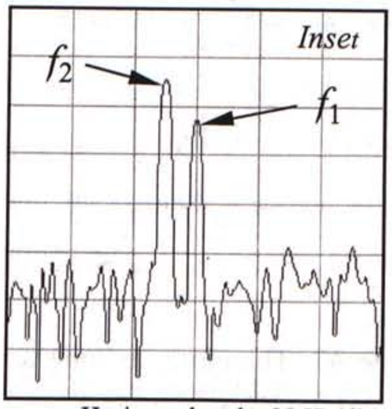


Figure 4.8: The inset shows the spectra measured at output fiber #5 for f_1 =100 Hz, f_2 =90 Hz, V_{pp} =0.5V (r =0.011). The power at the current ID (f_2) is ~7dB higher than the previous ID (f_1). Horizontal scale is 20 Hz/div, while the vertical scale is 10 dB/div.

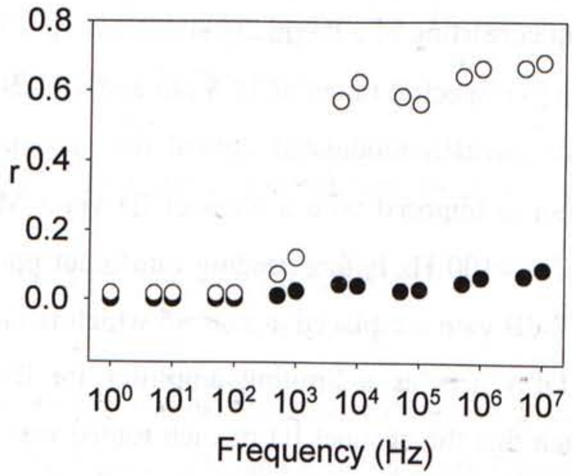


Figure 4.9: The optical modulation index ratio, r, versus frequency plot for two input modulation amplitudes of 0.1 (●) and 0.8 (○).

Figure 4.9 shows the measurements of r versus f for two different input modulation amplitudes, indicating that f is best limited to several hundred Hz as predicted by the lifetime of the EDFA. It should be noted that the channel ID with the smaller input amplitude generates a significantly smaller value in r, which can be explained by the failure of the EDFA to saturate the lower portion of a large signal.

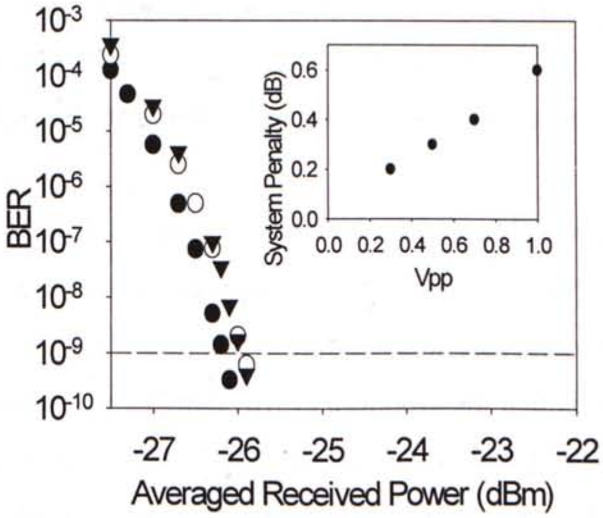


Figure 4.10: BER measurements for (•) direct transmission through OXC without ID, (○) transmission through OXC with one ID, and (▾) loop back configuration with two IDs. We used external modulated 1-Gb/s 2^{15}-1 NRZ PRBS at λ=1546.7 nm as the data channel and the channel ID is set at 100 Hz. System penalty for various values of V_{pp} is shown in the inset.

Figure 4.10 shows the BER measurements for the data channel for three cases: (1) direct transmission through AWG without channel ID; (2) transmission through AWG with one channel ID with V_{pp} = 0.5 V at f =100 Hz; and (3) loop back (cascaded) configuration with two channel IDs. A small degradation of ~0.2 dB in receiver sensitivity was observed at a BER of 10^{-9} with and without channel ID, but no degradation was found between the cases of single and dual channel IDs. System penalty variation as a function of V_{pp} was also studied for a range of $0.3 < V_{pp} < 1.0$ V (corresponding to $0.010 < r < 0.012$) at a BER of 10^{-9} (Figure 4.10 inset). The increase in power penalty is owed to the increase in residual amplitudes of the ID.

Discussion

The flatness of the saturation region of the EDFA is essential in this scheme. Reduction or elimination of the pilot tone is based on the fact that the output power would be constant in response to small amplitude variations in the input power. In our case, we had to use two EDFAs, the first is used to amplify the signal so that it operates in the saturation region of the second EDFA. But the saturation region of the second EDFA is not totally flat, resulting in some undesired power fluctuations at the output. What is needed is an amplifier with "hard limiting" characteristics [61]. Such an amplifier could replace the 2-amplifier setup presently used, provided that the input power was high enough.

The reason that we chose to use large amplitudes at low frequencies instead of small amplitudes at high frequencies is that the large amplitudes are easier to detect. The trade-off here is that the detection time is longer.

Also to be noted is that the dropping of wavelengths will result in diminishing the saturation effect that is needed to reduce or eliminate the pilot tone. Therefore, a monitoring channel will have to be used to keep the EDFA saturated.

Summary

In this section, a real-time optical-path surveillance scheme for OXC is proposed and demonstrated. The scheme is based on imposing RF pilot tones that serve as channel IDs to each wavelength channel inputted to the OXC. Optical-path routing error can be detected by comparing the channel ID with the routing information stored in the OXC.

4.4 Summary

In this chapter, we have proposed two surveillance schemes for OXCs in optically amplified wavelength routing networks. A typical dynamic wavelength routing network showing OXCs with attached end nodes is shown in Figure 4.11. The end nodes can be the hubs for local access networks. Because of fault-tolerance consideration and the one-way passage of EDFAs, there are two simplex links (in opposite directions) between any two connecting routing nodes. EDFAs are placed at the network branches to compensate for the fiber attenuation due to the long distance between routing nodes and the insertion loss of the routing nodes themselves. The routing switches in OXCs may suffer a slow degradation in performance through time or an abrupt discontinuity in service. Therefore, by adopting either proposed surveillance scheme, OXCs can be monitored and thus we can potentially obtain fault-free wavelength routing in all-optical wavelength routing networks, as any failure detection will result in the network manager rerouting traffic away from the failing points until the offending OXC is fixed.

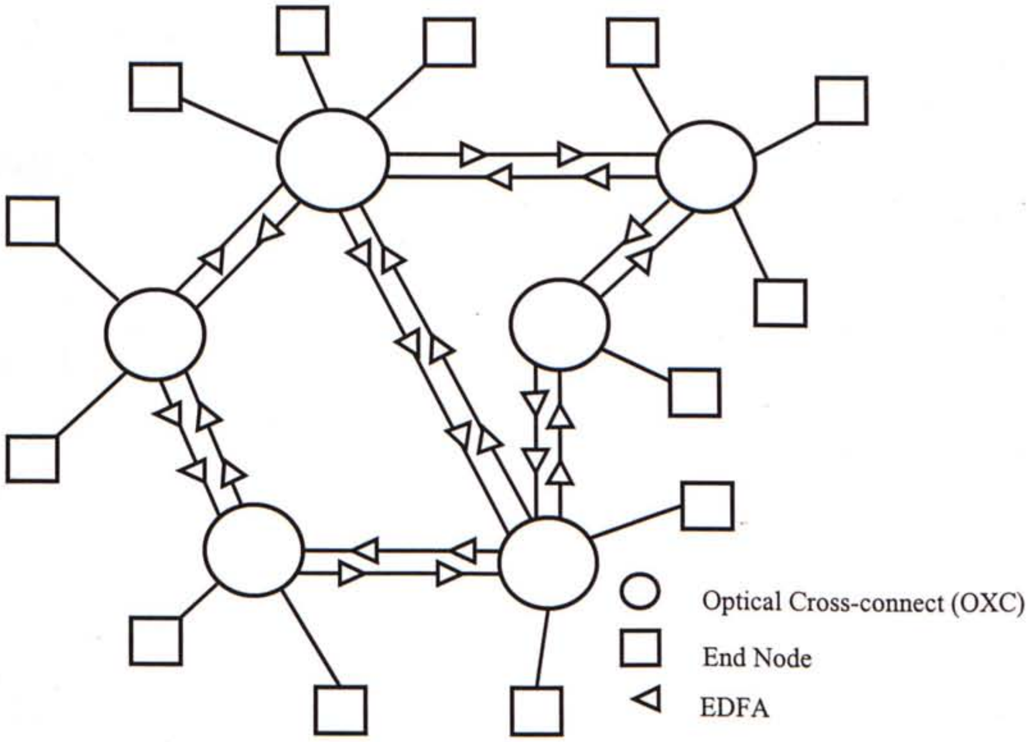


Figure 4.11: A typical wavelength routing network.

Chapter 5

Conclusion

5.1 Summary of the Thesis

The objective of this thesis is to explore a viable approach to achieve high-speed optical multi-access networks and also to investigate novel surveillance schemes for identifying optical path routing faults in optical cross-connects (OXC) for optically amplified wavelength routing networks.

Chapter 2 presented an overview of all-optical networks and multi-access networks. Their main features were briefly described. Also presented were some design consideration of all-optical multi-access networks with different multi-access techniques, including WDMA, TDMA and SCMA. Chapter 3 discussed a class of practical multi-access networks, called tunable-channel multi-access (TCMA) networks. The photonic implementation of a wavelength division TCMA network was proposed and experimentally demonstrated using a simplified network node data transmitter. An arrayed waveguide grating (AWG) is used to separate the wavelength channels, and a modulator on each wavelength channel allows for fast channel selection. On one channel, slot access is achieved by our proposed pilot tone signaling scheme and data packets are modulated into empty slots. The constructed data transmitter is designed to detect the Slot-Occupied pilot tone that indicates that a time slot is occupied with data.

In the absence of the pilot tone the transmitter will add 125 μs of data into the empty time slot. The constructed transmitter does not include the functions of the media access control unit, which encompasses wavelength channel selection and the processing of the Cycle-Start, Slot-Occupied and Data-Ready flags to control the M-SW switch that sends data to the modulators. But, the data transmitter circuit includes a splitter that will direct some of the tapped signal for Cycle-Start tone detection. It should be noted that the tone detection circuit needed to detect the Cycle-Start pilot tone would be similar to the one already constructed to detect the Slot-Occupied tone. Since the Cycle-Start and Slot-Occupied pilot tones can be reused, the data transmitter circuit can be identical for all the network nodes, ideal for mass production processes.

The design of the data transmitter circuit is sufficient to show the promising capabilities of the proposed architecture and ACTA media access control protocol. But in order to switch smaller sized data packets, the detection speed has to be increased. Potentially the switching speed can be about 100 ns, using the present 10 MHz pilot tone, but problems with noise require consecutive checks before the switch is closed. I believe that, with some improvements to the circuit board design, the noise can be reduced, eliminating the need for consecutive checks. At present, with the leakage and noise considerations, the network can probably support two fully functional nodes with the data adding function. If the leakage and noise restriction can be rectified, then the network will be much more scalable, supporting hundreds of network nodes depending on the optical modulation index of data.

Chapter 4 discussed two surveillance schemes for optical path routing fault identification in OXCs, where the optical path routing status can be monitored simultaneously and continuously without interrupting the in-service data channels. Also, neither scheme requires any additional light source for monitoring. In the first scheme, the residual unused amplified spontaneous emission (ASE) from optical amplifiers is used as the monitoring sources at each input fiber of the OXC. At each optical amplifier the ASE is modulated at a different low frequency that acts as the identification (ID) for that input port. Fiber Bragg gratings (FBGs) of different center wavelengths within the unused ASE region are placed at the output ports of the OXC to reflect the power of the modulated ASE to be analyzed. Presently this scheme may be too expensive to implement in real wavelength routing networks. For an N input port, N output port OXC, it will require N electronically-controlled Fabry-Perot filters and N circulators. Furthermore, if the same M wavelengths were inserted at the inputs, then $N \times M$ FBGs would be required to monitor the routing paths of all the wavelengths. The scheme would be more feasible by integrating the parts together using planar lightwave circuit (PLC) technology [62]. For instance, the Fabry-Perot filters could be integrated with the input EDFAs, while the circulators and the M FBGs at each output port could be integrated together as one component. As for the reliability of this scheme, the monitoring source created by the scanning Fabry-Perot filter reduces the amplification of the data channels, reducing the scalability of this scheme. The number of ports this scheme can monitor is also limited by the scanning limit of the Fabry-Perot filter and frequency spacing between ID frequencies. A limit of 12 kHz and a spacing of 200 Hz will limit the number of monitored ports to 60. The moving parts of the Fabry-Perot filter also compromise the reliability of this scheme, as they are more susceptible to failure and an observable hystersis effect.

The second approach involves the addition of frequency tones onto wavelength channels as channel identification. At the OXC output ports, the channel ID is tapped off to compare the detected physical connection and the switch-setting information stored in the routing control module. Gain-saturated optical amplifiers are used for ID removal at the output ports of the OXC. To implement this scheme, N extra modulators and EDFAs would be needed for an $N \times N$ OXC. Since only low frequency pilot tones are needed, cheap modulators can be chosen to cut costs. As for the two EDFA setup, PLC integration could make it feasible for this scheme to eventually contribute to a complete fault surveillance system for future optical amplified wavelength routing networks. Otherwise, this approach is very attractive. Most of it is based on very mature RF technology that is both cost-effective and highly reliable. The scalability of this scheme is limited by the residual tone, as the present setup can only reduce the tone. Since tone reduction is frequency dependent for any given modulation amplitude, the frequency limit is about 10 kHz for maximum scalability. At this limit, the number of ports that can be monitored with a frequency spacing of 10 Hz is in the hundreds. Note that the lower the frequency the longer the detection time.

5.2 Future Work

Optical implementations of wide area backbone networks have been researched extensively. Recently though, a need for an intermediate type network has generated much activity in the investigation of metropolitan-area-networks (MANs). MANs can operate over distances of ~50 km and at high data rates. Our next step is to implement our proposed tunable-channel multi-access network in a MAN environment. This work entails integrating the data transmitter circuit into a network card for use inside high-speed computers and building more nodes, including the all important head node. When such a network has been setup, its performance will be analyzed by looking at network characteristics such as delay and throughput of its operation. The delay may include the time required for channel tuning, propagation delay, and the message transmission time.

As for the optical cross-connect surveillance schemes, future work might include reducing the size of the monitoring setup by monolithically integrating the components with the OXC. This integration may also help to reduce the cost of implementing these schemes, as it is cheaper to produce the components together. Since the EDFAs play such a big part in both of these schemes, designing new EDFAs with the desired characteristics is an alternative direction to pursue.

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