Chapter 2

TECHNOLOGY AND ARCHITECTURE

The development of optical burst switching relies on the successful development of several key technologies, including all-optical switches, burst mode receivers, and optical wavelength converters. While development in these areas has progressed over the past several years, additional work may be required before such technology is available for use in practical systems. Regardless of what type of technology is eventually used in the design of optical burst-switched networks, network designers must stil take into consideration any physical-layer constraints imposed by the selected device and component technologies.

This chapter presents an architectural overview of optical burst switching nodes, focusing on the functional components needed for optical burst switching. We then present several key technologies for supporting the optical burst switching architecture and discuss various physical-layer issues that may affect the performance of optical burst-switched networks.

2.1 OBS Network Architecture

An optical burst-switched network consists of optical burst switching nodes that are interconnected via fiber links. Each fiber link capable of supporting multiple wavelength channels using wavelength division multiplexing (WDM). Nodes in an OBS network can either be *edge nodes* or *core nodes* as shown in Fig. 2.1. Edge nodes are responsible for assembling packets into bursts, and scheduling the bursts for transmission on outgoing wavelength channels. The core nodes are primarily responsible for switching bursts from input ports to output ports based on the burst header packets, and for handling burst contentions.

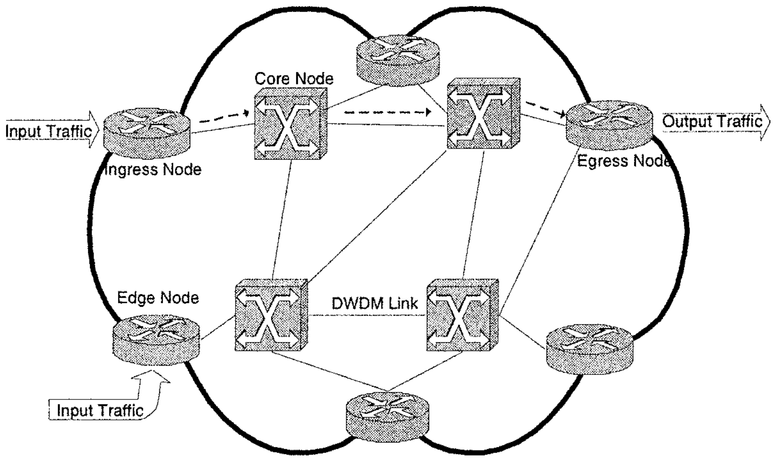

Figure 2.1. OBS Network Architecture

The ingress edge node assembles incoming packets from the client terminals into bursts. The assembled bursts are transmitted all-optically over OBS core routers without any storage at intermediate nodes within the core. The egress edge node, upon receiving the burst, disassembles the bursts into packets and forwards the packets to the destination client terminals. Basic architectures for core and edge routers in an OBS network have been studied in [13, 2, 3]. Figure 2.2, illustrates where various functionalities are implemented within an optical burst-switched network. The ingress edge node is responsible for burst assembly, routing, wavelength assignment, and scheduling of bursts at the edge. The core node is responsible for signaling, scheduling bursts on core links, and resolving contention. The egress edge node is primarily responsible for disassembling the burst and sending the packets up to the higher network layer.

In the network architecture, it can be assumed that each node can support both new input traffic as well as all-optical transit traffic. Hence, each node consists of both a core router and an edge router, as shown in Fig. 2.3 and Fig. 2.4.

The core routers (Fig. 2.3) consist of an optical cross connect (OXC) and a switch control unit (SCU). The SCU creates and maintains a forwarding table and is responsible for configuring the OXC [4]. When the SCU receives a burst header packet, it identifies the intended destination and consults the router signaling processor to find the intended output port. If the output port is available when the data burst arrives, the SCU configures the OXC to let the data burst pass through. If the port

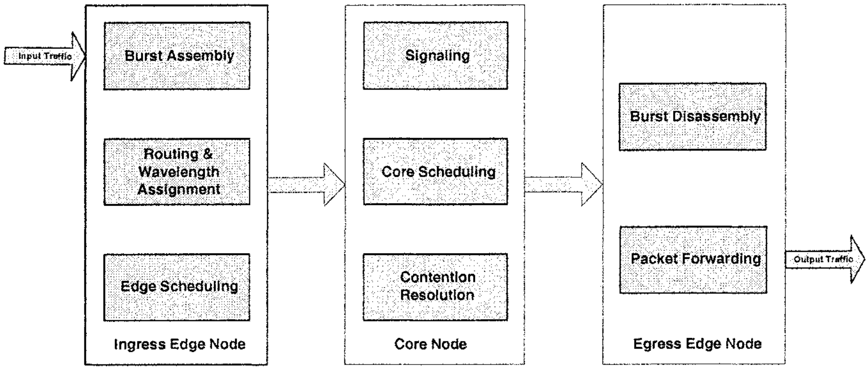

Figure 2.2. OBS functional diagram.

is not available, then the OXC is configured depending on the contention resolution policy implemented in the network. In general, the SCU is responsible for header interpretation, scheduling, collision detection and resolution, forwarding table lookup, switching matrix control, header rewrite, and wavelength conversion control. In the case of a data burst entering the OXC before its control packet, the burst is simply dropped (referred to as *early burst arrival problem*).

The edge router (Fig. 2.4) performs the functions of pre-sorting packets, buffering packets, assembling packets into burst, and disassembling bursts into its constituent packets. Different burst assembly policies, such as a threshold policy or a timer mechanism can be used to aggregate bursty data packets into optical bursts and to send the bursts into the network. The architecture of the edge router consists of a routing module (RM), a burst assembler, and a scheduler. The routing module selects the appropriate output port for each packet and sends each packet to the corresponding burst assembler module. Each burst assembler module assembles bursts consisting of packets which are headed for a specific egress router. In the burst assembler module, there is a separate packet queue for each class of traffic. The scheduler creates a burst based on the burst assembly technique and transmits the burst through the intended output port. At the egress router, a burst disassembly module disassembles the bursts into packets and send the packets to the upper network layers.

Some researchers have also proposed a more centralized OBS architecture, referred to as wavelength-routed optical burst switching (WR-OBS) [5]. A WR-OBS network combines the functions of OBS with fast circuit switching by dynamically assigning and releasing wavelength-routed lightpaths over a bufferless optical core. The potential advantages

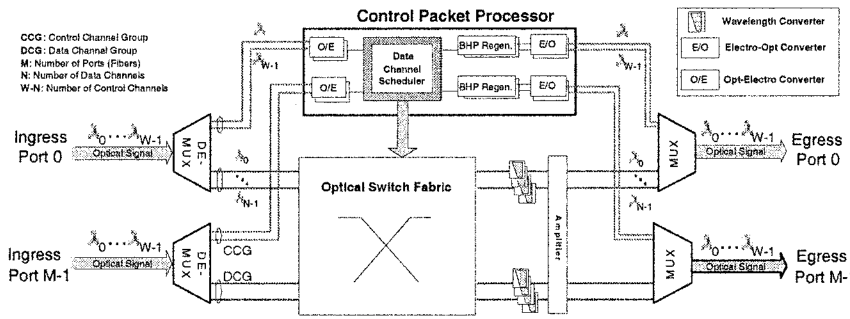

Figure 2.3. Architecture of Core Router.

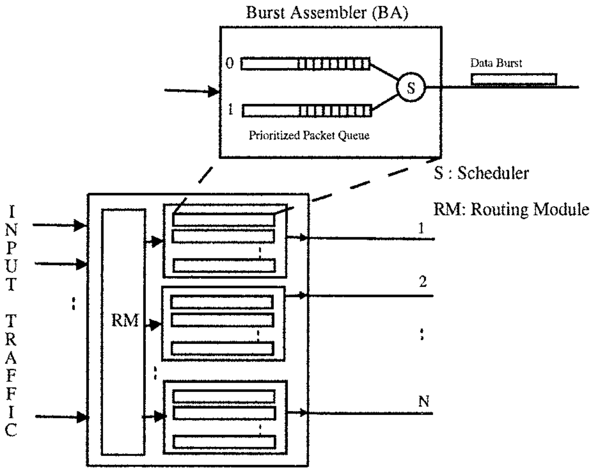

Figure 2.4. Architecture of Edge Router.

of this architecture compared to conventional OBS are explicit QoS provisioning. The benefits compared to static wavelength-routed optical networks (WRONs) are fast adaptation to dynamic traffic changes in optical networks and more efficient utilization of each wavelength channel.

In a WR-OBS network, a centralized request server is responsible for reserving resources for different connection request across the network. Each ingress node sends their connection request to the request server, where the requests are queued in based on their destination egress node and QoS class. The centralized server performs resource allocation based on its global knowledge of the status of every wavelength on every link in the entire network. The centralized request server is responsible for processing each individual connection request, calculating a route from the source of the request to the corresponding destination, and also reserving the requested number of wavelengths on every link along the path of the connection. The ingress edge node begins data transmission only after it receives a confirmation message from the request server. WR-OBS may improve network throughput, but the centralized nature of the design is not very scalable.

2.2 Enabling Technology

In order to provide basic optical burst switching functionality described in the previous section, several optical device technologies are required. In core and edge nodes, the OXC must be implemented using a fast optical switch fabric. The edge nodes must also have fast burst-mode receivers that are able to acquire the signal of an incoming burst quickly. Each node should also have some form of wavelength conversion in order to reduce contention on output links.

2.2.1 Optical Switching Technology

While OBS does not require switching times as fast as optical packet switching, fast switching times are nonetheless favorable. Currently, there are several different candidate technologies for performing all-optical switching.

One of the more mature device technologies for performing all-optical switching is micro-electromechanical systems (MEMS) technology. In MEMS switches, tiny movable mirrors are adjusted to direct light from a given input port to a given output port. One example of how MEMS switches can be designed is given in Fig. 2.5. In this design, the light from a given input fiber is directed to a mirror in an input mirror array. The mirror is adjusted to redirect the light to a mirror in an output mirror array which directs the light to the appropriate output fiber. Since MEMS rely on mechanical adjustment of mirrors to redirect light, switching times are somewhat slow. Typical switching times for MEMS switches are on the order of 50 ms.

A switching technology that offers faster switching times is the semiconductor optical amplifier (SOA) gate switch. The diagram of a basic SOA switch is show in Fig. 2.6. Light arriving on a given input is broadcast to multiple SOAs using an optical coupler. The SOAs act as gates that can either be switched on or off. If the SOA is switched on, the incoming signal is passed to the output, otherwise the signal is blocked. The advantages of SOA switches include a fast switching time on the order of 1 ns, and the possibility of multicasting a signal to multiple outputs. A disadvantage of SOA-based switches is that the couplers re-

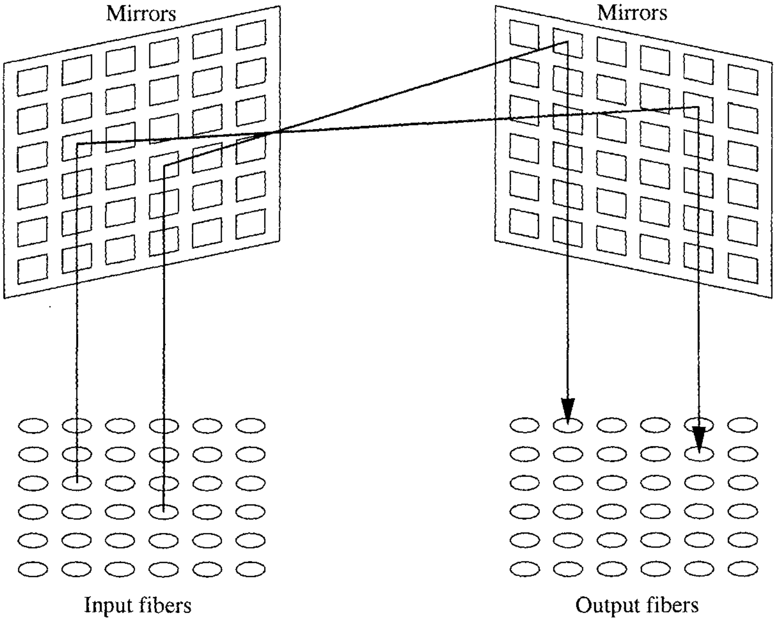

Figure 2.5. MEMS switch.

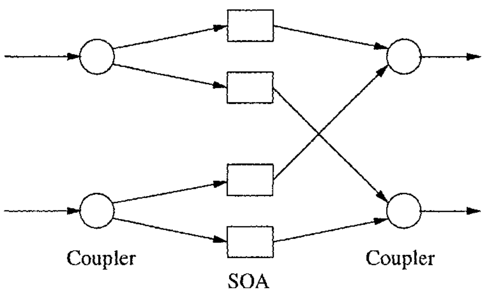

Figure 2.6. Semiconductor optical amplifier (SOA) switch.

sult in a reduction of signal power, possibly limiting the distances that signals can travel. Also, SOA devices tend to be expensive and have high polarization sensitivity [6].

2.2.2 Burst-Mode Receivers

Traditional receivers used in current optical transmission systems, such as SONET, are not well suited for optical burst switching. Such receivers assume constant phase and power for incoming signals and also assume that a signal is always present. In OBS networks, the bursts that arrive to a given receiver may have different phase and power, since the bursts may be arriving from different sources and may be traversing different paths through the network. Furthermore, due to the nature of bursts, a signal is only present for the duration of a burst.

Burst-mode receivers are receivers that are designed to adapt to the varying phase and power of incoming bursts. Another characteristic of burst-mode receivers is their fast clock acquisition time. Burst-mode receivers that are capable of recovering the clock of an incoming 2.5 Gb/s signal within 24 ns have been demonstrated in laboratory experiments [7].

2.2.3 Wavelength Conversion

In optical burst-switched networks which utilize WDM, it is desirable to have wavelength conversion capabilities at each node in order to reduce contention. The most straightforward way to convert a signal from one wavelength to another is to covert the optical signal to an electronic signal and to use the electronic signal to modulate an optical signal on the desired output wavelength. This method is fairly simple and can convert signals that are operating at rates of up to 10 Gb/s [8]; however, the approach is not transparent and requires the optical signal to have a specific modulation format and a specific bit rate.

One approach to performing all-optical wavelength conversion is cross-gain modulation. In cross-gain modulation, the data signal is sent through a semiconductor optical amplifier (SOA) along with a continuous wave (CW) pump signal on a different wavelength. When the data signal is high, the carriers in the gain region of the SOA become depleted, and the SOA enters saturation. As a result, the amplification for the CW signal is reduced. When the data signal is low, the CW signal receives full amplification. Thus, an inverted copy of the data will be imposed on the output signal. This technique is capable of converting signals that are operating at rates of up to 10 Gb/s. The limitation of cross-gain modulation based conversion techniques is these techniques require high input power for the data signal, and the output signal has a low extinction ratio (ratio of power for a '0' bit to the power for a '1' bit). This low extinction ratio results from the fact that, even when the SOA is in saturation, the CW signal is still receiving some amount of amplification.

Another method for providing optical wavelength conversion is by using four-wave mixing. Four-wave mixing is a nonlinear effect in which signals at frequencies f_1 and f_2 interact to create new frequency components at $2f_1 - f_2$ and $2f_2 - f_1$. If the data signal is operating at frequency f_1, and if a CW pump signal is operating at frequency f_2, then the data will be imposed on new optical signals at frequencies $2f_1 - f_2$ and $2f_2 - f_1$.

The newly generated signals have lower power than the input signals; thus, the conversion efficiency for this technique is not very high. Furthermore, the efficiency decreases as the difference between the pump wavelength and the output signal wavelength increases.

2.3 Physical-Layer Issues

When designing an optical burst switched network, many physical constraints must be taken into account. Some typical physical-layer issues include attenuation, dispersion, and fiber nonlinearities. While many of these issues apply to optical networks in general, several issues may raise particular concerns in optical burst-switched networks.

2.3.1 Attenuation

As an optical signal traverses fiber, the signal power decreases due to attenuation. Attenuation is a function of the wavelength of the signal and is caused primarily by absorption and Rayleigh scattering. Absorption is caused when the light incident on silica molecules or impurities in the fiber are absorbed. For most fibers, the amount of absorption for the range of useful wavelengths (between 0.8 and 1.6 μm) is negligible. Rayleigh scattering is caused when small variations in the refractive index of the fiber scatter the light.

In an optical burst-switched network, attenuation may limit the maximum distance that a burst can travel optically. In most cases, optical amplifiers can be used to overcome attenuation; however, optical amplifiers can also introduce noise.

2.3.2 Dispersion

If an optical signal consists of multiple wavelength components, then the different components of the signal will travel at different speeds, leading to the spreading of the signal in the time domain. This effect is known as dispersion. Forms of dispersion include modal dispersion and chromatic dispersion.

Modal dispersion is caused when multiple modes of the same signal propagate at different velocities along the fiber. Modal dispersion can be eliminated by using single-mode fiber. Single-mode fiber has sufficiently small core diameter that it captures only a single fundamental mode of the propagating signal.

Chromatic dispersion is caused as a result of the speed of light in a fiber being a function of the wavelength. Thus, if the transmitted signal consists of more than one wavelength component, certain wavelength components of the signal will propagate faster than other wavelength components, causing the signal to spread out in the time domain. Types of chromatic dispersion include material dispersion, in which the refractive index of fiber varies as a function of the wavelength, and waveguide dispersion, in which the refractive index for a particular wavelength depends on the fraction of power traveling in the core of the fiber and the fraction of power traveling in the cladding of a fiber.

For the case in which a signal consists of a pulse representing a single bit, dispersion causes the pulse to widen as it travels through a fiber. As a pulse widens, it can broaden enough to interfere with neighboring pulses (bits) on the fiber, leading to intersymbol interference. Dispersion thus limits the bit spacing and the maximum transmission rate on an optical fiber channel.

At 1300 nm, material dispersion in a conventional single-mode fiber is near zero. Fortunately, this is also a low attenuation window. Through advanced techniques such as *dispersion shifting*, fibers with zero dispersion at a specific wavelength between 1300 nm and 1700 nm can be manufactured [9]. In a dispersion-shifted fiber, the core and cladding are designed such that the waveguide dispersion is negative with respect to the material dispersion, thus canceling the total dispersion. However, the dispersion will only be zero for a single wavelength.

In addition to problems with intersymbol interference, dispersion may also introduce synchronization problems in optical burst-switched networks. In an optical burst-switched network, the burst header is typically sent on a different wavelength than the burst itself. Each of these wavelengths will experience different degrees of dispersion, causing the header and burst to either drift further apart or drift closer together in the time domain. If the physical distances of each link and the dispersion profile of the fiber are known, it may be possible to compensate for the dispersion by appropriately adjusting the offset at the source node.

2.3.3 Fiber Nonlinearities

Nonlinearities in fiber will typically have an effect on operating parameters, such as transmission rate, number of channels, channel spacing, and signal power. Examples of fiber nonlinearities include four-wave mixing, self-phase modulation, cross-phase modulation, stimulated Raman scattering, and stimulated Brillouin scattering.

Four-Wave Mixing (FWM) occurs when two wavelengths, operating at frequencies f_1 and f_2, respectively, mix to cause signals at $2f_1 - f_2$ and $2f_2 - f_1$. These extra signals, called sidebands, can cause interference if they overlap with frequencies used for data transmission. Likewise, mixing can occur between combinations of three or more wavelengths.

The effect of FWM in WDM systems can be reduced by using unequally-spaced channels [10].

Self-phase modulation is caused when changes in the intensity of a signal result in variations in the phase of a signal. The instantaneous variations in the phase of a signal can introduce additional frequency components in the signal. These additional frequency components, combined with the effects of dispersion, will lead to the spreading or compression of optical pulses in the time domain.

Cross-phase modulation is a shift in the phase of a signal caused by the change in intensity of a signal propagating at a different wavelength. Similar to self-phase modulation, the shifts in phase can introduce additional frequency components, leading to increased dispersion. Although cross-phase may limit the performance of optical communication systems, it may also have advantageous applications. Using cross-phase modulation, a signal on a given wavelength can be used to modulate a pump signal on a different wavelength. Such techniques can be used in wavelength conversion devices.

Stimulated Raman Scattering (SRS) is caused by the interaction of light with molecular vibrations. Light incident on the molecules creates scattered light at a longer wavelength than that of the incident light. A portion of the light traveling at each frequency in a Raman-active fiber is downshifted across a region of lower frequencies. The light generated at the lower frequencies is called the Stokes wave. The range of frequencies occupied by the Stokes wave is determined by the Raman gain spectrum which covers a range of around 40 THz below the frequency of the input light. In silica fiber, the Stokes wave has a maximum gain at a frequency of around 13.2 THz less than the input signal.

The fraction of power transferred to the Stokes wave grows rapidly as the power of the input signal is increased. Under very high input power, SRS will cause almost all of the power in the input signal to be transferred to the Stokes wave.

In multiwavelength systems, the shorter-wavelength channels will lose some power to each of the higher-wavelength channels within the Raman gain spectrum. To reduce the amount of loss, the power on each channel needs to be below a certain level. In [11], it is shown that in a 10-channel system with 10 nm channel spacing, the power on each channel should be kept below 3 mW to minimize the effects of SRS.

Stimulated Brillouin Scattering (SBS) is similar to SRS, except that the frequency shift is cause by acoustic interactions. In SBS, the shifted light propagates along the fiber in the opposite direction as the input signal. The intensity of the scattered light is much greater in SBS than in SRS, but the frequency range of SBS, on the order of 10 GHz, is much lower than that of SRS. Also, the gain bandwidth of SBS is only on the order of 100 MHz.

To counter the effects of SBS, one must ensure that the input power is below a certain threshold. Also, in multiwavelength systems, SBS may induce crosstalk between channels. Crosstalk will occur when two counter-propagating channels differ in frequency by the Brillouin shift, which is around 11 GHz for wavelengths at 1550 nm. However, the narrow gain bandwidth of SBS makes SBS crosstalk fairly easy to avoid.

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