Circuit Switching

Dr. Farid Farahmand and Dr. Qiong (Jo) Zhang, *Central Connecticut State University and Arizona State University at West Campus*

INTRODUCTION

The fundamental purpose of a communication system is to exchange information between two or more devices. Such system can be optimized for voice, data, or both. In its simplest form, a communication system can be established between two *nodes* (or *stations*) that are directly connected by some form of point-to-point transmission medium. A station may be a PC, telephone, fax machine, mainframe, or any other communicating device. This may, however, be impractical, if there are many geographically dispersed nodes or the communication requires dynamic connection between different nodes at various times.

An alternative method to a point-to-point connection is establishing a *communication network*. In a communication network, each communicating device (or station) is connected to a network node. The interconnected nodes are capable of transferring data between stations. Depending on the architecture and techniques used to transfer data, two basic categories of communication networks are *broadcast networks* and *switched networks*.

In broadcast networks, a single node transmits the information to all other nodes and hence, all stations will receive the data. A simple example of such network is a citizens' band (CB) radio system, in which all users tuned to the same channel can communicate with each other. Other examples of broadcast networks are satellite networks and Ethernet-based local area networks, where transmission by any station will propagates through the network and all other stations will receive the information.

In a switched network, the transmitted data is not passed on to the entire medium. Instead, data are transferred from source to destination through a series of intermediate nodes. Such nodes, often called *switching nodes*, are only concerned about how to move the data from one node to another until the data reaches its destination node. Switched communication networks can be categorized into different types such as the following:

- Circuit-switched networks.
- Packet-switched networks.
- Message-switched networks.
- Burst-switched networks.

In this chapter we focus on circuit-switched networks. In a circuit-switched network, also called line-switched network, a dedicated physical communication path is established between two stations through the switching nodes in the network. Hence, the end-to-end path from source to destination is a connected sequence of physical links between nodes and at each switching node the incoming data is switched to the appropriate outgoing link.

A circuit-switched communication system involves three phases: circuit establishment (setting up dedicated links between the source and destination); data transfer (transmitting the data between the source and destination); and circuit disconnect (removing the dedicated links). In circuit switching the connection path is established before data transmission begins. Therefore, the channel capacity must be reserved between the source and destination throughout the network and each node must have available internal switching capacity to handle the requested connection. Clearly, the switching nodes must have the intelligence to make proper allocations and to establish a route through the network. A more complete discussion comparing circuit switching, packet switching and message switching can be found in Chapter 74.

The most common example of a circuit-switched network can be found in public telephone network (PTN) supporting services such as POTS (plain old telephone systems) and long-distance calls. Other examples of circuit-switched services are integrated services digital network (ISDN), and switched 56, 64, and 384 (Kbps) services. The majority of wireless application protocols (WAP)–enabled phones also operate on top of circuit-switched networks. Furthermore, many public networks dedicated to data transport also use circuit-switching techniques; an example of a network in Europe is circuit-switched public data network (CSPDN), which transports data on circuit-switched networks using the X.21 protocol. Circuit switching also has wide applications in optical networks including wavelength division multiplexed (WDM) systems and WDM SONET networks.

With tremendous growth in data communications and Internet traffic in the past few decades, circuit-switching technology may appear to have lost its importance and in fact, many believe that it will eventually be replaced by more residual competitors such as packet switching. Many major telephone companies have considered spending billions of dollars to upgrade their switches to support packet switching. However, the existing $100 billion investment in the public telephone network in the United States makes such migration non-trivial. In fact, there seems to be a renewed interest in implementing circuit switching in optical networks as a result of the ease of building very high-capacity optical circuit switches and rapid reconfiguration around failure. For example, many researchers have proposed using circuit switching instead or in addition to packet switching at the core of the Internet where packet switching offers low link utilization.

In the remainder of this chapter we first examine the basic concepts of circuit switching networks and various switching technologies. Then, we look at different circuit-switched services. We briefly describe the general architecture of circuit-switched optical networks. We also investigate the performance of circuit-switched networks. Finally, we look at the future of circuit switching technology and its position in future applications.

CIRCUIT-SWITCHED NETWORKS

In this section we describe the elements of a circuit-switched network and examine their basic functionalities. Figure 1 shows a circuit-switched network. Three basic elements in this network are end-stations (or terminals), transmission media, and switching nodes. Through one or more switching nodes, end-stations can be temporarily interconnected to each other. A switching node can simply provide a transmission path between other switches and it may not be connected to any terminals; this is the case with Node C in Figure 1. In general, switching nodes in circuit-switched networks are the most invisible elements to the users and yet represent the most important elements in terms of offering available services.

Depending on the transmission technology and the physical transmission media over which connections take place, a switching node can be based on electrical (analog or digital) or optical technology. In the following paragraphs we first describe the main building blocks of a generic switching node and then examine various switching technologies.

Switching Node Architecture

In general, a switching node provides the following basic functionalities:

- signaling
- control
- switching
- interfacing

The basic function of the signaling element in a switching node is to monitor the activity of the incoming lines and to forward appropriate status or control information to the control element of the switch. Signaling is also used to place control signals onto outgoing lines under the direction of the control element. The control element processes incoming signaling information and sets up connections accordingly. The switching function itself is provided by a switching matrix (or fabric), which is an array of selectable cross-points used to complete connections between input lines and output lines, as shown in Figure 2a. The switching fabric can operate in the electrical or optical domain. The network interface provides the hardware required to connect different devices, such as analog, digital TDM lines, optical fibers, etc. to the switch matrix. These basic components of a switching node are depicted in Figure 26.

An important characteristic of a circuit-based switch is whether it is blocking or non-blocking (Stallings, 1999). Blocking occurs when the switching matrix does not allow some input lines to be connected to output lines.

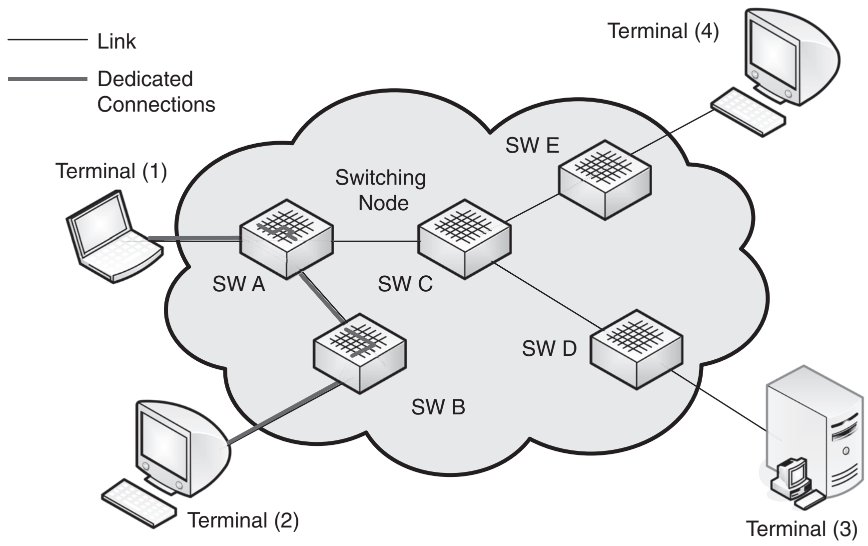

Figure 1: A circuit-switched network

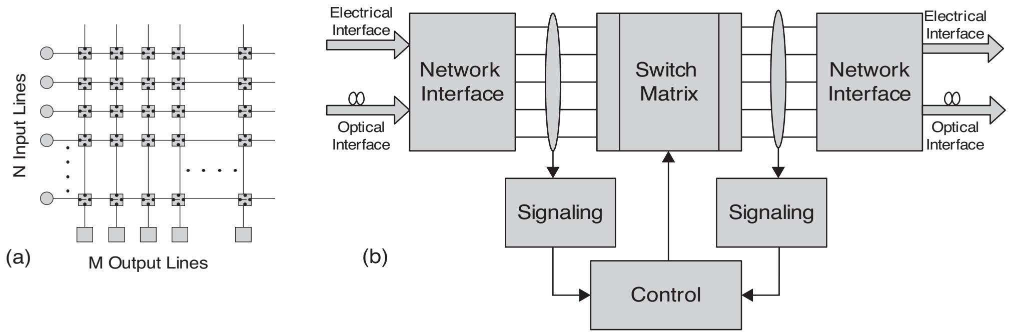

Figure 2: (a) An array of selectable cross-points, (b) switching node elements

Consequently, at the network level, some stations will not be able to be connected together. A non-blocking switching node, on the other hand, allows all inputs to be connected to all outputs. As a result, a network with non-blocking switching nodes permits all stations to be connected (in pairs) at once and grants all possible connection requests as long as the destination node is free. It is hence, desirable to have a non-blocking configuration, particularly in data communications. However, a major consideration is the high cost of non-blocking switching nodes. In fact, in many cases it is more practical to build blocking switches where the blocking probability is acceptable.

The switching function between the inputs and outputs in the matrix can be based on one or more of the following switching technologies:

- space-division
- time-division
- frequency-division
- wavelength-division

In the following sub-sections we briefly describe the characteristics of each switching technology.

Space-Division Switching

In space-division switching each input takes a different physical path in the switch matrix depending on the output. Hence, when a connection is established through a space switch matrix, a permanent physical contact is made on the matrix of cross-points. The connection will be maintained throughout the call duration. This technology can be primarily developed to accommodate analog transmission. Broadly speaking, space-division switching can be classified into three types: manual, electro-mechanical, and stored-program control.

Historically, circuit switching was designed for making standard telephone calls on the public telephone network. Hence, development of switching technology is traced back to the first commercial manual telephone switchboard used for public telephone network (the first manual switching machine started operating on January 2, 1878, in New Haven Connecticut, two years after the invention of the telephone, and it was only capable of supporting 21 subscribers (Bellamy, 2000). Every subscriber's line was terminated on the rear of the switchboard, while the front of the switchboard consisted of many loop jacks. Upon requesting a connection, the operator would manually connect the appropriate jacks using a loop cord with a loop plug on each end.

The second generation of space-division switching systems was electro-mechanical. Two common types of such systems were *step-by-step* (also known as the Strowger switch in honor of its inventor) and *crossbar* switches. Other types of electro-mechanical switches were All Relay, Panel, and X-Y systems; however, they were not as widely used.

A basic step-by-step switch has a single input terminal and multiple output terminals. Connection from the input terminal to the outputs is controlled by an internal rotary contact, or wiper. As the wiper rotates, it establishes a contact between the input and output terminals. Each time the user dials a rotary-dial digit, the rotary contact is advanced one position, and connects the input terminal to the next output terminal. This process continues until all digits are dialed (Chapuis, 1982; Clark, 1997). The principle of a step-by-step switch with a single input terminal and multiple output terminals is shown in Figure 3.

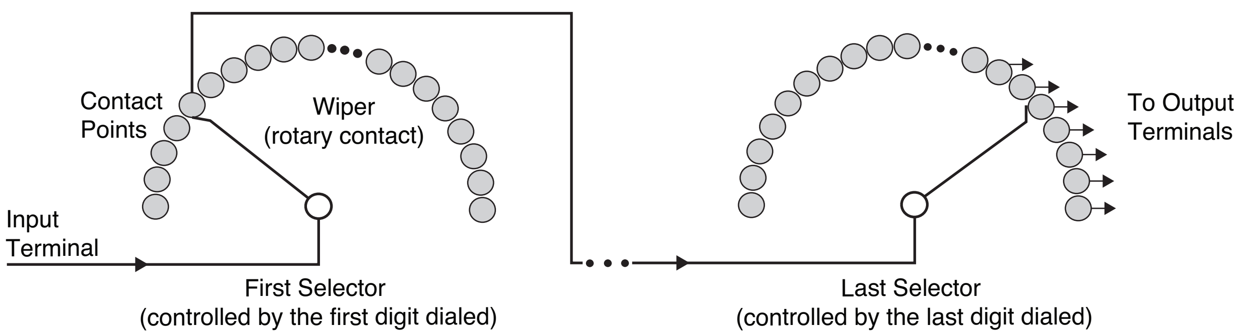

Figure 3: A step-by-step switch with a single input terminal and multiple output terminals

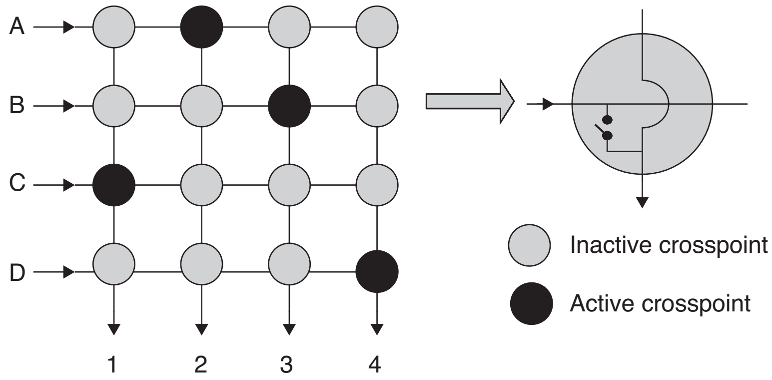

Figure 4: A crossbar switch with four incoming circuits, 4 outgoing circuits, and 16 switch cross-points

In a crossbar switch (also known as cross-point switch) as digits are dialed, the control element of the switch receives the entire address before processing it. The cross-points of the crossbar switch are mechanical contacts with magnets to setup and hold a connection. The term crossbar arises from the use of crossing horizontal and vertical bars to initially select the contacts on the cross-point. Once the circuit is established, the switching contacts are held by electromagnets energized with direct current passing through the established circuit. When the circuit is opened, the loss of current causes the cross-points to be released.

Figure 4 shows a crossbar switch with four incoming circuits, four outgoing circuits, and 16 switch cross-points, which may be active or inactive. Any of the incoming circuits can be interconnected to any one, and only one, of the outgoing circuits. The figure shows the simultaneous interconnections between the following circuits: A to 2, C to 1, D to 4, and B to 3. A typical internal design of the switch cross-point is also depicted in Figure 4.

Step-by-step and crossbar switching systems use electro-mechanical components for both switching matrix and control elements. In 1965, Bell Systems introduced the first computer-controlled switching system, known as No. 1 ESS (Electronics Switching System), which was used in the public telephone network (Martin, 1985). The electronic switching capability of No. 1 ESS was primarily referred to as the computer-controlled switching and not the nature of the switching matrix itself. In fact, the switching matrix was still using electro-mechanical reed relays (nickel-iron reeds sealed in a glass tube, which make contact as a result of magnetic field induced by coil around them). These switches were considered as the first stored-program control switch types used in the public telephone network.

Time-Division Switching

With the advents of digital technology and the development of pulse code modulation (PCM) both voice and data could be transmitted via digital signals. Digital technology led to a fundamental change in the design and architecture of switching systems. The need for time-division switching arises from the fact that digital signals are often carrying multiple individual circuits, or channels, in appropriate *timeslots* (TS). In such systems, when two different multiplexed channels are interconnected together through the switch matrix a *virtual circuit* is established. This is done by interchanging timeslots, each of which maintain partial contents of a particular channel. This operation is referred to as timeslot interchanging (TSI) (Stallings, 1999).

In a digital switch architecture, an incoming channel must be connected to a channel on any outgoing stream. A common architecture to achieve this utilizes both time-division switch capability, to shift channels between timeslots, and space-division switching capability, to enable a different physical outgoing line system to be selected. This architecture is referred to as time-space-time (TST).

Figure 5 shows a multistage time-space-time architecture to switch the timeslots of two digital line systems, each containing 24 time slots. The incoming signals are directly fed into the time switch, the output of which feeds the space switch in the middle. The output of the space switch feeds another time switch to which the outgoing

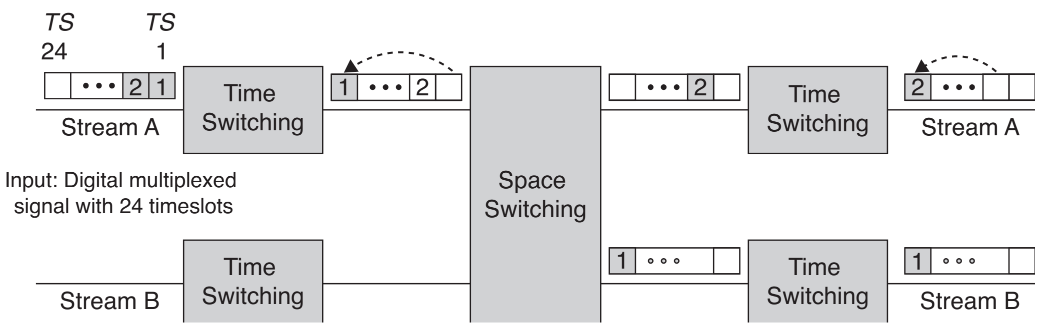

Figure 5: A time-space-time switch architecture, connecting channel 1 and 2 on incoming stream A to channel 24 on outgoing streams B and A, respectively

signals are connected. This figure shows timeslots (channels) 1 and 2 in incoming port (stream A) are switched to timeslot (channel) 24 in the outgoing stream B and A, respectively. Note that the second time switch stage is necessary to ensure that multiple timeslots in one incoming stream are not superimposed or blocked. Having more stages can further improve the switch performance. In addition to TST, some of the more common structures used in commercially available systems are TSSST, STS, SSTSS, TSTST.

The first time-division switching system deployed in the United States was the AT&T-designed No. 4 ESS, which was placed into service in 1976. The No. 4 ESS was considered as the first truly digital high-capacity switch adopted in the public telephone network. It implemented digital electronics in its control unit and switching matrix and was capable of serving a maximum of 53,760 circuits. Later, AT&T introduced No. 5 ESS, an improved version, handling 100,000 lines.

Frequency and Wavelength-Division Switching

Prior to full development of digital technology, telephone networks used frequency-division multiplexing (FDM) to carry several voice channels on a single physical circuit (e.g., a twisted cable). In these systems, multiple voice channels would be modulated onto carriers separated by some frequency spacing (e.g., 4 kHz). The composite signal, occupying the frequency range 60 to 108 kHz, was known as a group. In turn, five groups could themselves be multiplexed by a similar method into a super-group, containing 60 voice channels. Advances in FDM, allowed even higher levels of multiplexing, supporting transmission of hundreds of voice channels down a single connection.

Today, with the advances in optical networks, the same basic multiplexing principles used in FDM systems are being employed to optical signals. This is known as wavelength-division multiplexing (WDM). In fact, WDM is an analog multiplexing technique where the original signals are frequency shifted to occupy different portions of frequency spectrum of the transmission media. With the emergence of dense WDM (DWDM) system, 64 to 160 wavelengths (or channels) can be densely packed at 50 or 25 GHz intervals. Hence, the frequency and wavelength-division switching, in practice, are very similar. In the remaining of this section, we consider wavelength-division switching architecture (Toba, 1986).

WDM optical networks consist of optical switches, which are interconnected using WDM transmission systems. The basic functionality of the optical switch is to ensure that the data carried on any wavelength channel on any incoming optical link can be directed to any wavelength on any outgoing optical link. Based on the switching fabric technology, optical switches can be classified into two categories: *opaque* and *transparent* optical switches. An opaque optical switch, also called *optical cross-connect* (OXC), first, converts incoming optical signals to electrical signals, then, switches the electrical signals using an electronic switching fabric, and finally, converts the electrical signals back to optical signals at the output (Bernstein, 2003). A major disadvantage of such systems is that they need to perform multiple opto-electrical translations that can be both complex and expensive.

A transparent optical switch, also called *photonic cross-connect (PXC)*, on the other hand, does not require any opto-electrical translation and switches incoming signals in optical domain. The photonic switch fabric can be developed using a variety of technologies, including opto-mechanical, electro-optic, acousto-optic, thermal, micro-mechanical, liquid crystal, and semiconductor switch technologies. In practice, these technologies differ based on their performance characteristics such as switching speed, power loss as optical signals are switched, and wavelength independency in which switching is independent of the specific wavelength being switched. Figure 6 depicts a typical multistage photonic switch equipped with wavelength converters.

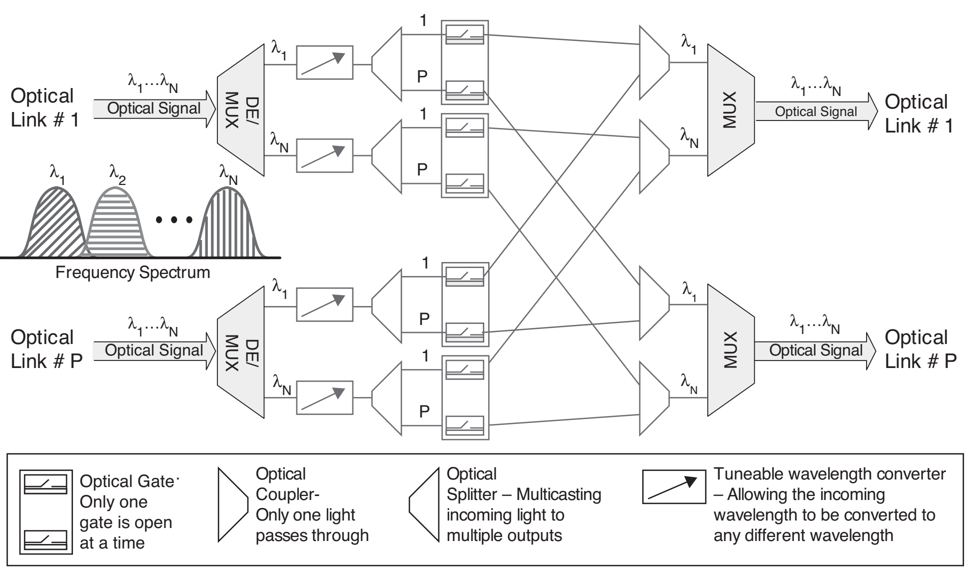

Figure 6: A typical optical switch architecture with wavelength converters, capable of supporting P incoming and outgoing optical links, each having N wavelength channels

Note that in this architecture, the photonic switch fabric is a matrix of optical gates. Similar architectures have been proposed and developed to eliminate the need for costly wavelength converters. With the current technology, control mechanism in the photonic switch fabrics is performed electronically.

Circuit-Switching Advantages and Disadvantages

Circuit switching was the dominant switching technology for more than 100 years. With such a long technological history, circuit switching is well understood, extremely well developed, and widely deployed in the form of the world wide public telephone system. Furthermore, advances in solid-state technology and micro-processors have led to constant improvement of capabilities of circuit-switching technology and, consequently, its cost effectiveness. In addition, new switching techniques, including wavelength-division switching, as well as high-speed signaling between switches, such as *common channel signaling CCS)*, have reduced average circuit setup delay and provided numerous new features.

In spite of emergence of newer switching technologies, namely packet switching, circuit-switching technology remains an appropriate and easily used technique with many unique advantages. One of the major advantages of circuit switching is that it is an essentially transparent service with no storage requirement. Once the connection is established, constant-rate data is provided to the connected stations. An important consequence of transparency is that no buffer overhead is required to accommodate data bursts that can be created by store-and-forward packet switching. Furthermore, the analog or digital data is passed through as-is from source to destination. Clearly, upon establishing the switched path, the time delay in delivering the data is only that resulting from speed-of-light delays, which are typically small compared to buffer delays, allowing real-time interaction between stations.

Circuit-switching technology also has major drawbacks, which make it less desirable for certain applications. A major issue with circuit switching is that all resources must be available and dedicated through the network between terminals before the communication takes place. Otherwise, the communication request will be blocked. This can result in potential channel inefficiency. For example, consider a case in which channel capacity is dedicated for the entire duration of a connection, however, no data is actually being transferred. For voice communications, since the idle times are minimum, high utilization can be expected. However, for data communications, since the capacity may be idle during most of the time of the connection (e.g., when we are only reading a downloaded Web page), circuit switching can result in relatively low utilization.

Another major issue with circuit switching is that in order to setup circuits between end-stations, circuit-switching facilities must be capable of processing large signaling at high-speed. Hence, existing systems may not be efficient for *bursty* traffic with short message durations and sporadic transmissions.

CIRCUIT-SWITCHING SERVICES

Today, the public telephone network remains, by far, the largest circuit-switched network in the world. As more data communication applications and services are emerged, it becomes critical to develop a technology that creates general integrated voice and data network that can be available to all users. This led to the development of integrated services digital networks (ISDN). In the remaining of this section we briefly describe examples of circuit-switched services as listed in Table 1.

Plain Old Telephone Service (POTS)

Prior to the existence of new types of networks, all communication systems had to be built based on the existing telecommunications facilities, which were largely oriented to what the common carriers refer to as plain old telephone service, known as POTS. The original POTS telephone network was designed and implemented to transfer analog voice signals. Consequently, even today, in order to use POTS for data communications, it is necessary to use a modem to convert the data to a form

Table 1: Examples of Circuit-Switched Services

Type of service	Bandwidth	Features
POTS	<64 Kbps	Adequate for transmitting text and low quality video; it is a dial-up connection requiring modem; limited by 3 to 4 KHz bandwidth.
Switched 56	64 Kbps	Dial-up connection requiring DSU/CSU; sufficient for low-resolution video; also used as backup facilities.
Leased Lines	64 Kbps to 274 Mbps	Dedicated lines; expensive but dependable and offer high quality connection. Typically, they are provisioned within the circuit-switched infrastructure for the duration of a lease.
ISDN	144 Kbps to 2 Mbps	End-to-end digital connectivity with different interfaces offering various bandwidths.
SONET	$N \times 51.84$ Mbps	Used with optical fibers; N = 1,3,12,48,192,768

suitable for voice-transmission media. Modem standards have been developed by ITU, formerly known as CCITT (*Comité Consultatif International Téléphonique et Télégraphique*), in the V-series Recommendations. Common examples of modem standards are V.32 (4.8 Kbps), V.34 (28.8 Kbps), V.42 (38.4 Kbps), and V.90 (56 Kbps).

The data transmission rate that can be obtained over a POTS connection is typically less than 64 Kbps. These rates are adequate for text and audio transmission. However, they are not sufficient for good quality video transmission in real-time. Video applications, such as video telephones, that operate over POTS often use small picture sizes in conjunction with image compression.

Switched 56 Service

Switched 56 service is a dial-up digital service provided by local and long distance telephone companies. For a connection, a data service unit/data channel unit (DSU/CSU) is used instead of a modem. Switched 56 service uses a 64 Kbps channel, but one bit per byte is used for band signaling, leaving 56 Kbps for data. This service allows the transmission of information over one or two twisted cable pairs to multiple points at a data rate of 56 Kpbs. Switched 56 service is ideally suited for use as a backup facility to leased lines where, if a break is detected in the leased line service, the data service unit (DSU) will automatically re-establish a connection using the switched 56 dial-up facility. This service is most cost-efficient for individuals and businesses that require moderate-volume file transfers, but do not need to have a permanent connection to all their locations.

Leased Lines

A leased line is a dedicated communication line that an individual or business can own and does not share with any other users. As a result, leased lines are highly dependable and offer high quality connections. Leased lines are excellent for providing required quality of service (QoS) for the transmission of delay and bandwidth-sensitive applications such as multimedia information (Sharda, 1999). However, the main disadvantage of leased lines is the high cost. Leased lines can be analog or digital.

Analog Leased Lines

This type of access is often used for network usage with full-time connectivity requirement. An analog leased line does not require any dial-up procedure. In addition, it provides higher quality connection and higher signal-to-noise ratio, leading to higher data transmission rate as compared to those on dial-up lines.

Digital Leased Lines

The digital leased line access is often used for large networks serving many users and requiring a high level of reliability. The digital leased lines offer various bandwidths. Common examples of digital leased lines in the United States, Japan, and Korea are fractional T1 (FT1), T1, T2, T3, and T4. T1 is a dedicated connection supporting data rates of 1.544 Mbps. A T1 digital line consists of 24 individual channels, each of which supports 64 Kbps. Each 64-Kbps channel, referred to as DS0, can be configured to carry voice or data traffic. The framing specification used in transmitting digital signals in Europe is called E1, which operates at 2.108 Mbps and contains 32 DS0 channels. Other levels of digital transmission are T2, T3, etc., which allow digital transmission at higher line rates.

Table 2: Various Digital Leased Lines and Their Bandwidths

Line type	Bandwidth	Application
Switched 384	384 Kbps	High quality video conferencing
T1	1.544 Mbps	Compressed video
T2	6.312 Mbps	Broadcast TV quality compressed video
T3	44.70 Mbps	HDVT-quality video transmission
T4	274.0 Mbps	Multiple video channels

In addition to the above rates, many telephone companies offer fractions of individual channels available in a standard T1 line, known as fractional T1 access. Bit rates offered by a fractional leased line can be 64 Kbps (one channel), 128 Kbps (2 channels), 256 Kbps (4 channels), 384 Kbps (6 channels), 512 Kbps (8 channels), and 768 Kbps (12 channels), with 384 Kbps (1/4 T1), and 768 Kbps (1/2 T1), also known as Switched 384 service and Switched 768 service, being the most common. Switched 384 service is particularly common for supporting high volumes of data and multimedia applications. Table 2 lists various digital leased lines along with their bandwidth and common multimedia applications.

Integrated Services Digital Network (ISDN)

The ISDN was designed in the 1980s to offer end-to-end digital connectivity, while providing the required QoS with data rates in the range of Kbps to Mbps over switched connections. ISDN also offers a more economical alternative to digital leased lines. In order to provide even higher data rates, the original ISDN was extended to broadband ISDN (BISDN) (Martin, 1985).

The ISDN services are provided to users as ISDN interfaces, each comprising a number of ISDN channels. Using 64-Kbps channels, called bearer or B channels, ISDN provides access to the digital network. ISDN provides lower error rate compared to typical voiceband modems and a relatively high bandwidth data channel. On the other hand, ISDN uses 16-Kbps or 64-Kbps signaling D channels to access the signaling network, which allows features such as accessing packet switching network, user-to-user message transfer, and simultaneous signal processing while having active connections. A very attractive application of signal accessing is to provide end-users the flexibility to dynamically reconfigure virtual private networks within the public network and have them interoperate with private facilities without a loss

Table 3: ISDN Interfaces

Interface type	Channels	Bandwidth	Application
Basic-rate interface	2B + D	144–192 Kbps	Digital voice and data
Primary-rate interface	23B + D or 30B + D	1.544 or 2.048 Mbps	Multimedia and LAN to LAN connection
Hybrid interface	A + C	Analog voice and 16 Kbps data	Hybrid connection for transition period

of features. Other ISDN channels are A and C, providing access to POTS and low speed digital data transmission, respectively.

ISDN channels (A, B, C, D) are combined to provide standard interfaces: basic rate interface (BRI), primary rate interface (PRI), and hybrid interface. Table 3 lists these interfaces with their channels and common applications.

Basic Rate Interface (BRI): Basic rate access provides two clear 64-Kbps information channels and one 16-Kbps signaling channel (2B + D), given the total information rate of 144 Kbps. Each of the B channels can be used independently of the other, supporting simultaneous voice and digital data communications.

Primary Rate Interface (PRI): Primary rate interface gives an information transfer capability of 1.544 Mbps. The bandwidth can be configured in a variety of ways including having 23 B channels plus one D channel to connect a number of devices to an ISDN network via, for example, a PBX. PRI in Europe is available as a 2.048-Mbps connection with 30 B channels and one D channel.

Hybrid Interface: The hybrid interface allows connections that use a hybrid of analog and digital communications. This interface has been included in the ISDN systems to provide a transition path from the old POTS service to digital services.

Synchronous Optical Network (SONET)

The synchronous optical network (SONET) is a multiplexing system similar to conventional time-division multiplexing. However, SONET was developed to be used with optical fibers. SONET systems are common examples of optical circuit-switched networks, which offer high-speed communications (we will discuss these networks in the next section). The lowest level of SONET hierarchy is the basic SONET signal referred to as the synchronous transport signal level-1 (STS-1). STS-1 has a 51.84 Mbps synchronous frame structure compromised of 28 DS-1 signals. Each DS-1 signal is equivalent to a single 24-channel T1 digital line. Thus, one STS-1 system can carry 672 individual 64-Kbps voice or data channels (24x28). With STS-1, it is possible to extract or add individual DS-1 signals without completely disassembling the entire frame.

Higher level signals are referred to as STS-N signals. An STS-N signal is composed of N byte-interleaved STS-1 signals. The optical counterpart of each STS-N signal is an optical carrier level–N signal (OC-N). Although, the SONET specification is primarily concerned with OC-N interconnect standards, electrical signals within the SONET hierarchy are used for interconnecting network elements operating at lower rates. Common values of N are 1, 3, 12, 48, 192, and 768. An interesting feature of SONET frames is that they have constant period. That is, an OC-3 (155 Mbps) frame has the same 125 microsecond period as an OC-768 (40 Gbps) frame, although the OC-768 frame carries a much larger payload. This period corresponds to the 8-KHz sampling period (and clock rate) of the first PCM-based quasi-digital networks.

OPTICAL CIRCUIT SWITCHING

In early generations of circuit-switching, circuits were established over copper wires and traversed a number of electronic circuit switching nodes. As the demand for network bandwidth increased, copper wire was (and continues to be) replaced by optical fiber, which provides significantly more bandwidth. The bandwidth of optical fiber can be further exploited through the use of WDM technology.

An optical circuit-switching network is similar to the example shown in Figure 1. In an optical network, however, transmission media are WDM links and switching nodes are optical (opaque or transparent). Using WDM transmission technology, the optical transmission spectrum is carved up into a number of over-lapping wavelength bands. Each wavelength band can support a single communication channel operating at the peak electronic rate. Today, the majority of optical networks deployed in long-distance telecommunication networks are point-to-point DWDM SONET networks, where each node requires optical-electronic-optical (O-E-O) conversions and electronic switching.

As we mentioned before, in an optical network that utilizes photonic cross-connects (PXCs), all circuits over the network are established in the optical domain. End-to-end all-optical circuits offering bandwidth equivalent to the bandwidth provided by a single wavelength, are referred to as *lightpaths*. Such optical networks are called *wavelength-routed* WDM networks (Mukherjee, 2006; Ramaswami, 2001). If wavelengths cannot be converted from one wavelength to another at PXCs, then the same wavelength must be used on all links of a lightpath. This requirement is known as the *wavelength continuity constraint*. Figure 7 shows a wavelength-routed network with three lightpaths established. Lightpaths cannot share the same wavelength on the same link. Hence, the lightpath between source 1 and destination 1 and the lightpath

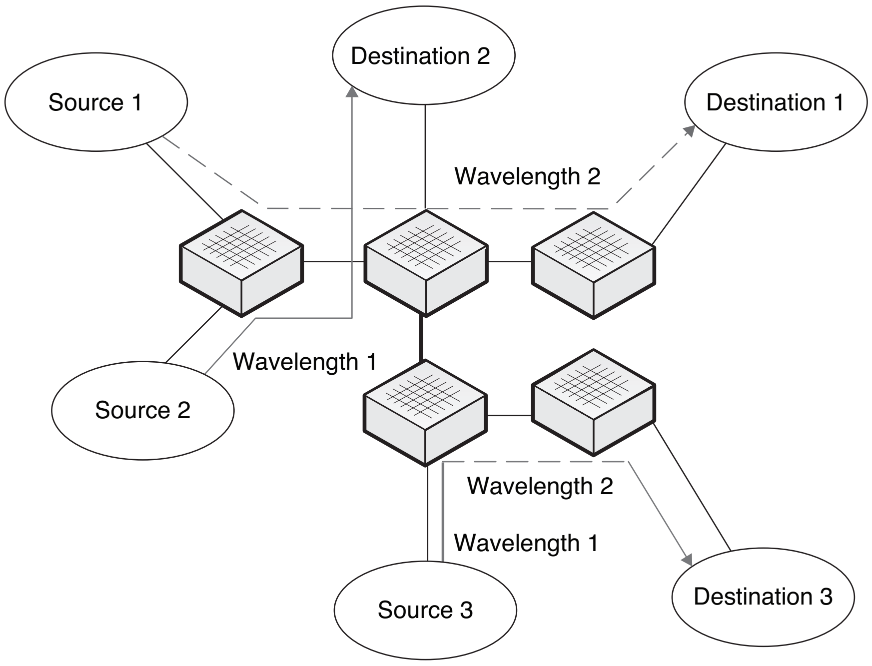

Figure 7: Wavelength-Routed WDM Network

between source 2 and destination 2 use different wavelengths. The lightpath between source destination 3 utilizes two different wavelengths without wavelength continuity constraint. This can be achieved using wavelength converters at intermediate nodes.

A key challenge in the practical implementation of optical networks is to develop efficient algorithms and protocols for establishing lightpaths (Zang, 2001). Such algorithms must select routes and assign wavelengths to all-optical circuits in a manner that efficiently utilizes network resources. Furthermore, signaling protocols must set up a lightpath in a timely manner, and must properly distribute control messages and network state information. In emerging optical networks, signaling and control for connection establishment may be implemented by one of three methods. First, it may be done within the generalized mulitprotocol label switching (GMPLS) framework. GMPLS defines the control architecture for establishing circuits, is based on MPLS in IP networks, and is primarily a construct supported by router vendors. A second approach uses the ASON ITU standards and has been put forward primarily within the carrier and telecom community. Finally, some research networks support a centralized control scheme that allows advanced reservation and scheduling of dedicated bandwidth.

CIRCUIT-SWITCHED NETWORK PERFORMANCE

When circuits are established, such as establishment of a phone call or a lightpath in a WDM network, the primary performance metrics of interest in circuit-switched networks are delay and blocking. Delay, or connection set-up time, refers to the time required to establish the circuit. Blocking occurs when there are insufficient resources along a given route to support an incoming circuit request. Blocking is often measured in terms of the blocking probability, which is the probability that an incoming call will be rejected due to the lack of resources.

Delay Analysis

Figure 8 depicts the transmission of data (a message) across four nodes in a circuit-switched network. The primary components of delay in circuit switching are the propagation delay of the signaling message on each link (D_p), the processing delay of the signaling message at each node (D_n), and the transmission delay of data traffic (D_t); for example it takes 0.1 second to transmit a 10,000 bit message onto a 100 Kbps line.

As shown in the figure, before the data (or message) is sent, a certain amount of elapsed time is required to setup the path. First, a setup message is sent through the network to setup a connection to the destination. Processing delay is the time spent at each node setting up the route of the connection.

Once the destination receives the call request, assuming the destination is not busy, it will return an acceptance message. On the return path, no processing delay at intermediate nodes will be required since the connections are already set up. This operation is referred to as *forward reservation*. In *reverse reservation*, however, the setup message will be directly sent to the destination and resource reservation at intermediate nodes occurs as the acceptance message is received; this is to avoid any resource reservation before ensuring that the end-to-end path is available. After the connection is set up, the message is sent as a single block, and the delay at the switching nodes will be negligible. Eventually, following the completion of data transmission, a release message will be sent requesting removal of all connections along the path.

Figure 8 also shows a case where an intermediate node (SW A) rejects a connection request. Note that in this case there is no need to propagate the setup message further to downstream nodes.

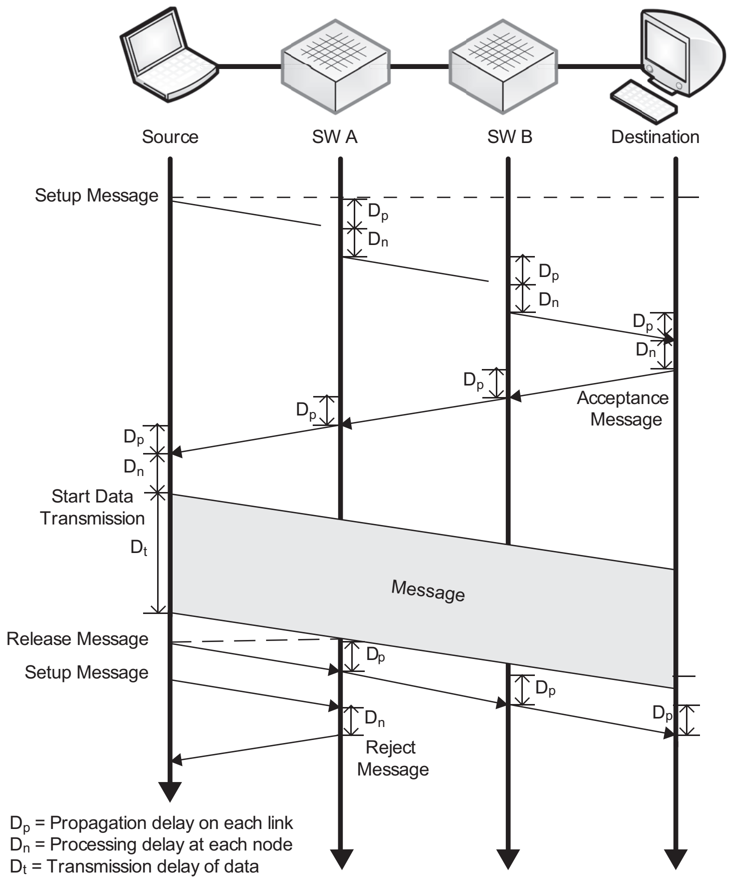

Figure 8: Event Timing Diagram in Circuit-Switched Networks

The total delay prior to transmission of data, as shown in Figure 8, will be $h(2D_p + D_n) + Dn$, where h is the number of hops on the end-to-end path; in our example $h = 3$. This delay is referred to as circuit setup delay. If data transmission delay (D_t) is smaller or equal to the setup delay, circuit switching will not be efficient and it results in low utilization. However, if D_t is much larger than the setup delay, then circuit switching can offer high utilization.

Blocking Probability Analysis

In traditional telephony applications, blocking probability can be analyzed by using standard queuing theory techniques. The simplest model is one in which we evaluate a single link in the network and assume that the call arrival rate is Poisson and the call-holding time is exponentially distributed. The assumptions of Poisson arrivals and exponential holding times are standard in the analysis of telecommunications systems and have been found to accurately model the behavior of voice calls.

More complicated blocking models have been developed by evaluating the blocking probability along the entire path of a call rather than on a single link. In such models, there is some degree of statistical dependence among links in the network. It is often sufficient and much simpler to assume that the links along an end-to-end path are statistically independent of one another. The limitation of such an assumption is a less accurate estimation of the blocking probability.

Single Link Blocking Model

When analyzing the call blocking probability on a single communication link (e.g., the link between SW A and SW B in Figure 8), we assume that the link is capable of supporting C connections, simultaneously (in the case of WDM networks, C can be the number of wavelengths supported by each optical link). Furthermore, we assume that calls arrive (or lightpath requests) according to a Poisson process with rate λ calls per second, and the call holding time (or lightpath duration) is exponentially distributed with an average holding time of $1/\mu$ seconds. Calls are assumed to be independent of each other. Under these assumptions, the link may be modeled as an *M/M/C/C* queuing system (Schwartz, 1986) and the probability that there are n calls in progress is given by:

$$p(n) = \frac{\frac{1}{n!}\left(\frac{\lambda}{\mu}\right)^n}{\sum_{k=0}^{C}\left(\frac{1}{k!}\left(\frac{\lambda}{\mu}\right)^k\right)}.$$

An arriving request will be blocked if there are already C calls in progress. Thus, the probability that a call is blocked on the link is given by:

$$p(C) = \frac{\frac{1}{C!}\left(\frac{\lambda}{\mu}\right)^C}{\sum_{k=0}^{C}\left(\frac{1}{k!}\left(\frac{\lambda}{\mu}\right)^k\right)}.$$

This equation is referred to as the *Erlang B* formula.

Path Blocking Model

In addition to calculating the blocking probability on a given link, it is also possible to estimate the blocking probability of a given end-to-end connection request for a call traversing multiple links (e.g., the path from source to destination in Figure 8, passing through three links). One approach is to model each link in a path as an *M/M/C/C* system. We define the arrival rate of connection requests from source node s to destination node d as λ^{sd} calls per second, the arrival rate of connections on link (i, j) as λ_{ij} calls per second, and the route taken by a connection from s to d as $R(s, d)$.

The offered load on a given link, λ_{ij}, can be calculated by adding the traffic from all source-destination pairs that route traffic over link (i, j):

$$\lambda_{ij} = \sum_{s,d:(i,j)\in R(s,d)} \lambda^{sd}.$$

To simplify the analysis, it is assumed that links are independent of one another. Furthermore, we assume call arrivals are Poisson and call holding times are exponentially distributed with an average holding time of $1/\mu$ seconds. In order for a connection request from s to d to succeed, spare capacity must be available on all links along the route. Alternatively, a connection will be blocked if at least one link in the connection's route has no available capacity. The blocking probability of a request from s to d can then be written as:

$$p(s,d) = 1 - \prod_{(i,j)\in R(s,d)} (1 - p_{ij}(C)),$$

in which

$$p_{ij}(C) = \frac{\frac{1}{C!}\left(\frac{\lambda_{ij}}{\mu}\right)^C}{\sum_{k=0}^{C}\left(\frac{1}{k!}\left(\frac{\lambda_{ij}}{\mu}\right)^k\right)}.$$

We now consider a simple example in which we calculate the path blocking probability. In this example, we assume that an end-to-end connection traverses two links. The total load on each link is known. Using the single link blocking model, we can obtain the blocking probability on each link, say p_1 and p_2. Hence the path blocking probability for the connection will be $1-(1-p_1)(1-p_2)$.

In the above analysis, we assumed that a connection request on any one of the C channels of any incoming link can be connected to any channel on any outgoing link.When the switching operation is performed in the electrical domain, such an assumption is rather trivial. However, in optical networks with PXCs, wavelength converters are required to guarantee such an assumption. Additional analytical models have been developed to calculate blocking probability in optical networks when no wavelength conversion is utilized (Barry, 1996).

FUTURE OF CIRCUIT SWITCHING TECHNOLOGY

The past half century, packet switching technology has advanced tremendously and turned into a major competitor for circuit switching. In fact, packet switching has become the dominant technology for data networks, including the Internet. Not surprisingly, many telephone companies have been willing to spend billions of dollars to upgrade their networks to support packet switching, potentially phasing out their circuit-switched based equipments.

However, many researchers and engineers have been investigating the implementation of circuit switching technology in wide area networks (WAN) and optical networks. In fact, circuit-switching technology has been considered as the practical approach in deploying future optical WDM networks. This is mainly a result of the fact that development of all-optical packet switching networks still lacks reliable optical buffers and synchronization techniques. Today, with the current technology, circuit switching is seen as a viable solution to establish transparent optical paths (lightpaths) providing large amounts of bandwidth. The key challenge, however, is to ensure circuit switching can be made rapidly adaptive to traffic fluctuation and connection requests. While many issues related to circuit switching and lightpath establishment have been studied in detail, control plane techniques for setting up optical paths are still under active development.

In emerging core networks, applications are expected to have a wider range of QoS requirements than in existing networks. Bandwidth-intensive applications, such as video on demand, video conferencing, scheduled bulk-file transfer, and grid computing are expected to have strict transmission-completion requirements coupled with high bandwidth requirements. Telemedicine has both high bandwidth and extremely tight jitter requirements. For many such applications, best-effort packet-switched networks are incapable of providing the required services. Therefore, circuit switching in core networks (e.g., core of the Internet) may be expected not only to support static logical links for higher-layer packet switched protocols, but also provide resources directly to end users and applications. Hence, performance of the Internet where circuit switching is implemented at the core, the adaptability of circuit switching to existing Internet protocols, such as TCP/IP, and many other similar open issues require detailed study (Molinero-Fernández, 2003).

Furthermore, many in the telecommunications community strongly favor circuit switching over development of new packet-based services, due to existing huge investments in circuit-switched networks and their readiness. They question the wisdom of focusing on introducing new switching technologies and protocols, and consequently developing new expensive equipments. Instead, they argue that we must gain more in-depth technical knowledge and develop smarter encoding and transmission techniques, which will work just fine with our existing well-functioning circuit-switched networks (Cringely, 2004).

CONCLUSION

In this chapter, we described the basic principles of circuit-switching technology. We discussed the building blocks of circuit-switched networks and examined its characteristics. We looked at advantages and disadvantages of circuit-switched networks and briefly explained its applications in providing different services. We also examined the basic concepts of circuit-based optical networks and described their operations. Future applications of circuit-switching technology were also outlined in this chapter. We examined various view points and research proposals, which emphasize the importance of circuit switching technology, particularly, in optical networks and core networks.

GLOSSARY

Bell System: This is an informal name given to the U.S. telecommunications company American Telephone & Telegraph Company (AT&T) before AT&T divested its local exchange telephone service operating companies on January 1, 1984.

CCITT: Short for Comité Consultatif International Téléphonique et Télégraphique, an organization based in Geneva, Switzerland, that sets international communications standards. CCITT changed its name to International Telecommunications Union (ITU), the parent organization, on March 1, 1993.

Citizens' Band Radio (CB): In the United States, it is a system of short-distance radio communication between individuals on a selection of 40 channels within the single 27 MHz (11 meter) band. CB does not require a license and unlike amateur radio can be used for commercial communications.

Common Channel Signaling (CCS): An out-of-band signaling method in which one channel of a communications link is used for carrying signaling for establishment and tear down of calls. The remaining channels are used entirely for the transmission of voice or data.

Data Service Unit/Data Channel Unit (DSU/CSU): A digital interface that provides the physical connection to the digital carrier network.

Frequency-Division Multiplexing (FDM): A scheme in which numerous signals are combined for transmission on a single communications line or channel. Each signal is assigned a different frequency (sub-channel) within the main channel.

Multi Protocol Label Switching (MPLS): A method used to increase the speed of network traffic flow by inserting information about a specific path the packet is taking to reach its destination. Hence, the router is no longer required to lookup the next node address. MPLS is multiprotocol in that it works with IP, ATM, and frame relay communications methods.

Protocol: A formal and pre-agreed set of rules that govern the communications between two or more entities. The protocol determines the meaning of specific values occurring in specific positions in the stream, the type of error checking to be used, the data compression method, how the sender will indicate that it has finished sending a message, and how the receiver will indicate that it has received a message.

Pulse Code Modulation (PCM): A way to convert sound or analog information to binary information (0s and 1s) by taking samples of the sound and recording the resulting number as binary information.

Quality of Service (QoS): It refers to the capability of a network to provide better service to selected network traffic over various technologies. The primary goal of QoS is to provide priority including dedicated bandwidth, controlled jitter and latency (required by some real-time and interactive traffic), and improved loss characteristics.

Time Division Multiplexing (TDM): A scheme in which numerous signals are combined for transmission on a single communications line or channel. Each signal is broken up into many segments, each having very short duration.

Wireless Application Protocol (WAP): A set of communication protocol standards to make accessing online services via handheld wireless devices such as mobile phones, pagers, two-way radios, Smartphones, and communicators.

REFERENCES

Stallings, William. 1999. *Data and Computer Communications*, 7th ed. Upper Saddle River, NJ: Prentice Hall.

Bellamy, John C. 2000. *Digital Telephony*, 3rd ed. New York, NY: John Wiley & Sons.

Chapuis, Robert J. 1982. *100 Years of Telephone Switching (1878–1978), Part 1: Manual and Electromechanical Switching (1878–1960s)*. Amsterdam, Holland: North-Holland Publishing Company.

Clark, Martin P. 1997. *Networks and Telecommunications*, 2nd ed. New York, NY: John Wiley & Sons.

Tomasi, Wayne. 2004. *Introduction to Data Communications and Networking*. Upper Saddle River, NJ: Prentice Hall.

Martin, James. 1985. *Telecommunications and the Computer*. Englewood Cliffs, NJ: Prentice-Hall.

Telephone Switch Timeline. http://www.dmine.com/phworld/switch/timeline.htm (accessed June 1, 2006)

Sharda, Nalin. 1999. Multimedia networks: fundamentals and future directions. *Communications of the Association for Information Systems*, 1. http://cais.isworld.org/articles/1-10/article.pdf (accessed April 27, 2007).

Toba, Hiromu, Kyo Inoue, and Kiyoshi Nosu. 1986. A conceptional design on optical frequency-division-multiplexing distribution systems with optical tunable filters. *IEEE Journal on Selected Areas in Communications*, 4(9):1458–67.

Schwartz, Mischa. 1986. *Telecommunication Networks: Protocols, Modeling and Analysis*. Boston, MA: Addison-Wesley Longman Publishing Co.

Zang, Hui, Jason P. Jue, Laxman Sahasrabuddhe, Ramu Ramamurthy, and Biswanath Mukherjee. 2001. Dynamic lightpath establishment in wavelength-routed WDM networks. *IEEE Communications Magazine*, 39(9):100–8.

Bernstein, Greg, Bala Rajagopalan, and Debanjan Saha. 2003. *Optical Network Control: Architecture, Protocols, and Standards*, 1st ed. Boston, MA: Addison-Wesley Professional.

Barry, Richard A. and Pierre A. Humblet. 1996. Models of blocking probability in all-optical networks with and without wavelength changers. *IEEE Journal on Selected Areas in Communications*, 14(5):858–67.

Mukherjee, Biswanath. 2005. *Optical WDM Networks*, New York, NY: Springer.

Ramaswami, Rajiv and Kumar Sivarajan. 2001. *Optical Networks: A Practical Perspective*, 2nd ed. San Francisco, CA: Morgan Kaufmann.

Ramaswami, Rajiv and Kumar Sivarajan. 1995. Routing and wavelength assignment in all-optical networks. *IEEE/ACM Transactions on Networking*, 3(5):489–500.

Baroni, Stefano and Polina Bayvel. 1997. Wavelength requirements in arbitrary connected wavelength-routed optical networks. *IEEE/OSA Journal of Lightwave Technology*, 15(2):242–51.

Cringely, Robert X. 2004. Out of Sight, Out of Mind. Big Old Stupid Telephone Companies Are Throwing Away Their Only Real Asset. http://www.pbs.org/cringely/pulpit/pulpit20040624.html (accessed April 27, 2007).

Molinero-Fernández, Pablo and Nick McKeown. 2003. The performance of circuit switching in the Internet. *OSA Journal of Optical Networking*, 2(4):83–96.

FURTHER READING

Since the invention of telephone in 1876, circuit switching has been the dominant switching technology. With such long history, volumes of materials have been dedicated to understanding properties of circuit-switching technology, its architecture, and performance. A comprehensive description of circuit switching technology and its properties can be found in Stallings (1999), Bellamy (2000), and Chapuis (1982). Chapuis (1982) and Clark (1997) provide detail descriptions on switching node architecture and various technologies used in circuit switching nodes. Detailed discussions on frequency and wavelength-division multiplexing are provided in Toba (1986).

Various online articles, including Tomasi (2004), Martin (1985), and Telephone (2006), offer valuable information regarding development of public telephone network and POTs. Applications of circuit switching technology pertaining multimedia services are discussed in Sharda (1999). Tomasi (2004) and Martin (1985) offer excellent discussions on ISDN technology.

Abundant materials are available on optical networking, SONET, and WDM systems. Interested reader can refer to Bernstein (2003), Mukherjee (2006), and Ramaswami (2001) for a complete treatment of these topics. Good surveys describing more advanced topics, such as wavelength routing, and impact of wavelength continuity constraints, can be found in Zang (2001), Ramaswami (1995), and Baroni (1997).

A comprehensive treatment of circuit switching performance is provided in Schwartz (1986). Discussion regarding the performance of optical networks can be found in Barry (1996). Finally, interesting discussions regarding possibility of using circuit switching technology at the core can be found in Molinero-Fernández (2003). Cringely (2004) provides a good argument as to why circuit switching must be maintained as the future switching technology for telephone companies.