CHAPTER 17

SONET/SDH

In this chapter, we introduce a wide area network (WAN), SONET, that is used as a transport network to carry loads from other WANs. We first discuss SONET as a protocol, and we then show how SONET networks can be constructed from the standards defined in the protocol.

The high bandwidths of fiber-optic cable are suitable for today's high-data-rate technologies (such as video conferencing) and for carrying large numbers of lower-rate technologies at the same time. For this reason, the importance of fiber optics grows in conjunction with the development of technologies requiring high data rates or wide bandwidths for transmission. With their prominence came a need for standardization. The United States (ANSI) and Europe (ITU-T) have responded by defining standards that, though independent, are fundamentally similar and ultimately compatible. The ANSI standard is called the **Synchronous Optical Network (SONET).** The ITU-T standard is called the **Synchronous Digital Hierarchy (SDH).**

> **SONET was developed by ANSI; SDH was developed by ITU-T.**

SONET/SDH is a synchronous network using synchronous TDM multiplexing. All clocks in the system are locked to a master clock.

17.1   ARCHITECTURE

Let us first introduce the architecture of a SONET system: signals, devices, and connections.

Signals

SONET defines a hierarchy of electrical signaling levels called **synchronous transport signals (STSs).** Each STS level (STS-1 to STS-192) supports a certain data rate, specified in megabits per second (see Table 17.1). The corresponding optical signals are called **optical carriers (OCs).** SDH specifies a similar system called a **synchronous transport module (STM).** STM is intended to be compatible with existing European

hierarchies, such as E lines, and with STS levels. To this end, the lowest STM level, STM-1, is defined as 155.520 Mbps, which is exactly equal to STS-3.

Table 17.1   *SONET/SDH rates*

STS	*OC*	*Rate (Mbps)*	*STM*
STS-1	OC-1	51.840	
STS-3	OC-3	155.520	**STM-1**
STS-9	OC-9	466.560	**STM-3**
STS-12	OC-12	622.080	**STM-4**
STS-18	OC-18	933.120	**STM-6**
STS-24	OC-24	1244.160	**STM-8**
STS-36	OC-36	1866.230	**STM-12**
STS-48	OC-48	2488.320	**STM-16**
STS-96	OC-96	4976.640	**STM-32**
STS-192	OC-192	9953.280	**STM-64**

A glance through Table 17.1 reveals some interesting points. First, the lowest level in this hierarchy has a data rate of 51.840 Mbps, which is greater than that of the DS-3 service (44.736 Mbps). In fact, the STS-1 is designed to accommodate data rates equivalent to those of the DS-3. The difference in capacity is provided to handle the overhead needs of the optical system.

Second, the STS-3 rate is exactly three times the STS-1 rate; and the STS-9 rate is exactly one-half the STS-18 rate. These relationships mean that 18 STS-1 channels can be multiplexed into one STS-18, six STS-3 channels can be multiplexed into one STS-18, and so on.

SONET Devices

Figure 17.1 shows a simple link using SONET devices. SONET transmission relies on three basic devices: STS multiplexers/demultiplexers, regenerators, add/drop multiplexers and terminals.
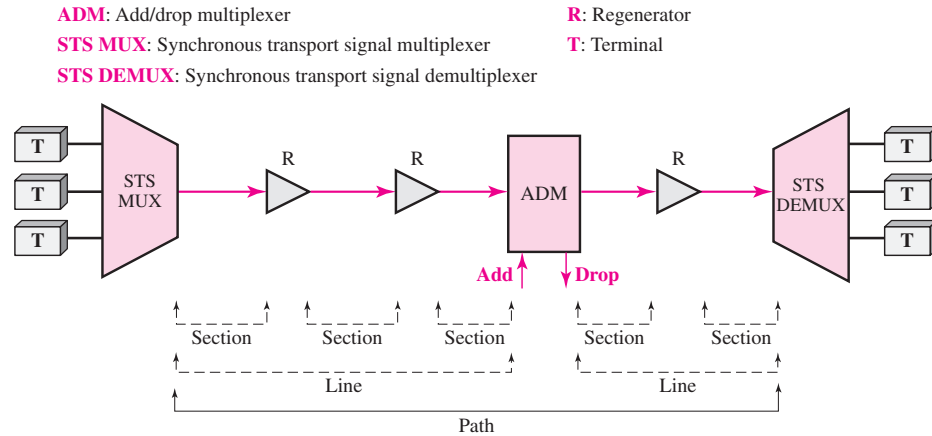
STS Multiplexer/Demultiplexer

STS multiplexers/demultiplexers mark the beginning points and endpoints of a SONET link. They provide the interface between an electrical tributary network and the optical network. An **STS multiplexer** multiplexes signals from multiple electrical sources and creates the corresponding OC signal. An **STS demultiplexer** demultiplexes an optical OC signal into corresponding electric signals.

Regenerator

Regenerators extend the length of the links. A **regenerator** is a repeater (see Chapter 15) that takes a received optical signal (OC-*n*), demodulates it into the corresponding electric signal (STS-*n*), regenerates the electric signal, and finally modulates the electric

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Figure 17.1   *A simple network using SONET equipment*

signal into its correspondent OC-*n* signal. A SONET regenerator replaces some of the existing overhead information (header information) with new information.

Add/drop Multiplexer

Add/drop multiplexers allow insertion and extraction of signals. An **add/drop multiplexer (ADM)** can add STSs coming from different sources into a given path or can remove a desired signal from a path and redirect it without demultiplexing the entire signal. Instead of relying on timing and bit positions, add/drop multiplexers use header information such as addresses and pointers (described later in this section) to identify individual streams.

In the simple configuration shown by Figure 17.1, a number of incoming electronic signals are fed into an STS multiplexer, where they are combined into a single optical signal. The optical signal is transmitted to a regenerator, where it is recreated without the noise it has picked up in transit. The regenerated signals from a number of sources are then fed into an add/drop multiplexer. The add/drop multiplexer reorganizes these signals, if necessary, and sends them out as directed by information in the data frames. These remultiplexed signals are sent to another regenerator and from there to the receiving STS demultiplexer, where they are returned to a format usable by the receiving links.

Terminals

A **terminal** is a device that uses the services of a SONET network. For example, in the Internet, a terminal can be a router that needs to send packets to another router at the other side of a SONET network.

Connections

The devices defined in the previous section are connected using *sections, lines,* and *paths*.

Sections

A **section** is the optical link connecting two neighbor devices: multiplexer to multiplexer, multiplexer to regenerator, or regenerator to regenerator.

Lines

A **line** is the portion of the network between two multiplexers: STS multiplexer to add/drop multiplexer, two add/drop multiplexers, or two STS multiplexers.

Paths

A **path** is the end-to-end portion of the network between two STS multiplexers. In a simple SONET of two STS multiplexers linked directly to each other, the section, line, and path are the same.

17.2   SONET LAYERS

The SONET standard includes four functional layers: the photonic, the section, the line, and the path layer. They correspond to both the physical and the data link layers (see Figure 17.2). The headers added to the frame at the various layers are discussed later in this chapter.

> **SONET defines four layers: path, line, section, and photonic.**

Figure 17.2   *SONET layers compared with OSI or the Internet layers*
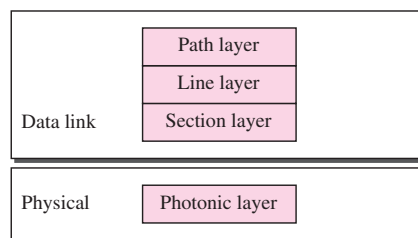
Path Layer

The **path layer** is responsible for the movement of a signal from its optical source to its optical destination. At the optical source, the signal is changed from an electronic form into an optical form, multiplexed with other signals, and encapsulated in a frame. At the optical destination, the received frame is demultiplexed, and the individual optical signals are changed back into their electronic forms. Path layer overhead is added at this layer. STS multiplexers provide path layer functions.

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Line Layer

The **line layer** is responsible for the movement of a signal across a physical line. Line layer overhead is added to the frame at this layer. STS multiplexers and add/drop multiplexers provide line layer functions.

Section Layer

The **section layer** is responsible for the movement of a signal across a physical section. It handles framing, scrambling, and error control. Section layer overhead is added to the frame at this layer.
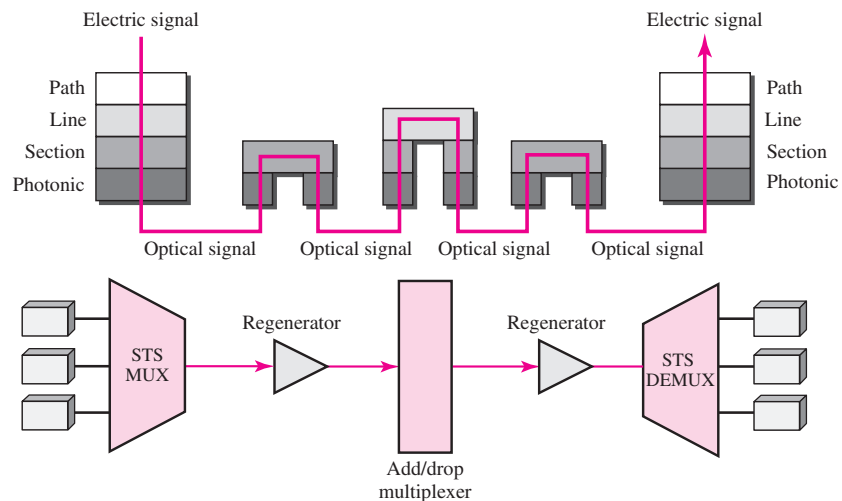
Photonic Layer

The **photonic layer** corresponds to the physical layer of the OSI model. It includes physical specifications for the optical fiber channel, the sensitivity of the receiver, multiplexing functions, and so on. SONET uses NRZ encoding with the presence of light representing 1 and the absence of light representing 0.

Device–Layer Relationships

Figure 17.3 shows the relationship between the devices used in SONET transmission and the four layers of the standard. As you can see, an STS multiplexer is a four-layer device. An add/drop multiplexer is a three-layer device. A regenerator is a two-layer device.

Figure 17.3   *Device–layer relationship in SONET*

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17.3   SONET FRAMES

Each synchronous transfer signal STS-*n* is composed of 8000 frames. Each frame is a two-dimensional matrix of bytes with 9 rows by $90 \times n$ columns. For example, STS-1 frame is 9 rows by 90 columns (810 bytes), and an STS-3 is 9 rows by 270 columns (2430 bytes). Figure 17.4 shows the general format of an STS-1 and an STS-*n*.

Figure 17.4   *An STS-1 and an STS-n frame*

a. STS-1 frame

b. STS-*n* frame
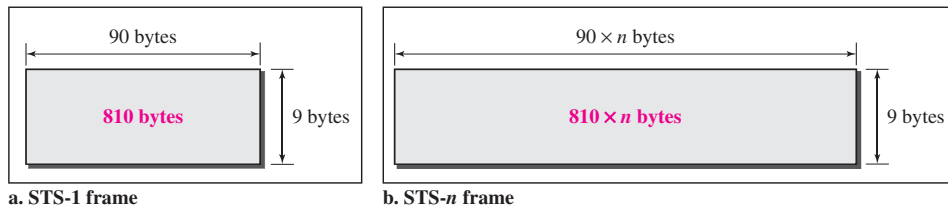
Frame, Byte, and Bit Transmission

One of the interesting points about SONET is that each STS-*n* signal is transmitted at a fixed rate of 8000 frames per second. This is the rate at which voice is digitized (see Chapter 4). For each frame the bytes are transmitted from the left to the right, top to the bottom. For each byte, the bits are transmitted from the most significant to the least significant (left to right). Figure 17.5 shows the order of frame and byte transmission.

Figure 17.5   *STS-1 frames in transition*

a. Byte transmission

b. Frame transmission
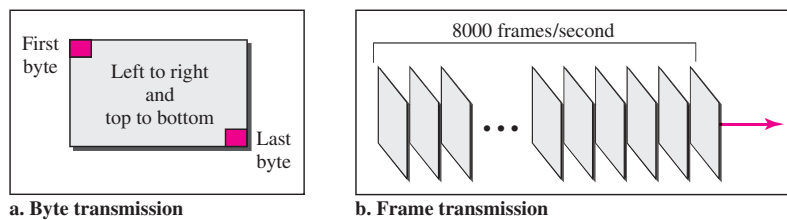
A SONET STS-*n* signal is transmitted at 8000 frames per second.

If we sample a voice signal and use 8 bits (1 byte) for each sample, we can say that each byte in a SONET frame can carry information from a digitized voice channel. In other words, an STS-1 signal can carry 774 voice channels simultaneously (810 minus required bytes for overhead).

Each byte in a SONET frame can carry a digitized voice channel.

Example 17.1

Find the data rate of an STS-1 signal.

Solution

STS-1, like other STS signals, sends 8000 frames per second. Each STS-1 frame is made of 9 by (1×90) bytes. Each byte is made of 8 bits. The data rate is

$$\text{STS-1 data rate} = 8000 \times 9 \times (1 \times 90) \times 8 = 51.840 \text{ Mbps}$$

Example 17.2

Find the data rate of an STS-3 signal.

Solution

STS-3, like other STS signals, sends 8000 frames per second. Each STS-3 frame is made of 9 by (3×90) bytes. Each byte is made of 8 bits. The data rate is

$$\text{STS-3 data rate} = 8000 \times 9 \times (3 \times 90) \times 8 = 155.52 \text{ Mbps}$$

Note that in SONET, there is an exact relationship between the data rates of different STS signals. We could have found the data rate of STS-3 by using the data rate of STS-1 (multiply the latter by 3).

> **In SONET, the data rate of an STS-n signal is n times the data rate of an STS-1 signals.**

Example 17.3

What is the duration of an STS-1 frame? STS-3 frame? STS-n frame?

Solution

In SONET, 8000 frames are sent per second. This means that the duration of an STS-1, STS-3, or STS-n frame is the same and equal to 1/8000 s, or 125 μs.

> **In SONET, the duration of any frame is 125 μs.**

STS-1 Frame Format

The basic format of an STS-1 frame is shown in Figure 17.6. As we said before, a SONET frame is a matrix of 9 rows of 90 bytes (octets) each, for a total of 810 bytes.

The first three columns of the frame are used for section and line overhead. The upper three rows of the first three columns are used for **section overhead (SOH).** The lower six are **line overhead (LOH).** The rest of the frame is called the synchronous payload envelope (SPE). It contains user data and **path overhead (POH)** needed at the user data level. We will discuss the format of the SPE shortly.

Section Overhead

The section overhead consists of nine octets. The labels, functions, and organization of these octets are shown in Figure 17.7.

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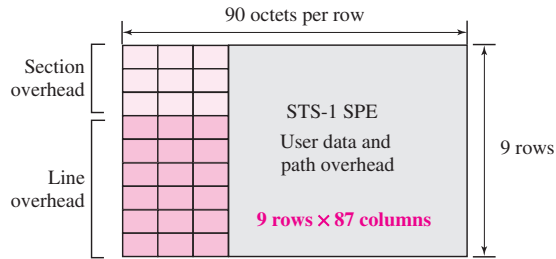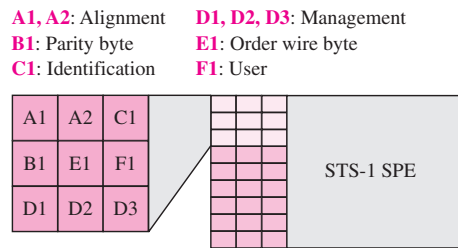**Figure 17.6**   *STS-1 frame overheads*

Figure 17.7   *STS-1 frame: section overhead*

❏ **Alignment bytes (A1 and A2).** Bytes A1 and A2 are used for framing and synchronization and are called alignment bytes. These bytes alert a receiver that a frame is arriving and give the receiver a predetermined bit pattern on which to synchronize. The bit patterns for these two bytes in hexadecimal are 0xF628. The bytes serve as a flag.

❏ **Section parity byte (B1).** Byte B1 is for bit interleaved parity (BIP-8). Its value is calculated over all bytes of the previous frame. In other words, the ith bit of this byte is the parity bit calculated over all ith bits of the previous STS-n frame. The value of this byte is filled only for the first STS-1 in an STS-n frame. In other words, although an STS-n frame has n B1 bytes, as we will see later, only the first byte has this value; the rest are filled with 0s.

❏ **Identification byte (C1).** Byte C1 carries the identity of the STS-1 frame. This byte is necessary when multiple STS-1s are multiplexed to create a higher-rate STS (STS-3, STS-9, STS-12, etc.). Information in this byte allows the various signals to be recognized easily upon demultiplexing. For example, in an STS-3 signal, the value of the C1 byte is 1 for the first STS-1; it is 2 for the second; and it is 3 for the third.

❏ **Management bytes (D1, D2, and D3).** Bytes D1, D2, and D3 together form a 192-kbps channel ($3 \times 8000 \times 8$) called the data communication channel. This channel is required for operation, administration, and maintenance (OA&M) signaling.

❏ **Order wire byte (E1).** Byte E1 is the order wire byte. Order wire bytes in consecutive frames form a channel of 64 kbps (8000 frames per second times 8 bits per

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frame). This channel is used for communication between regenerators, or between terminals and regenerators.
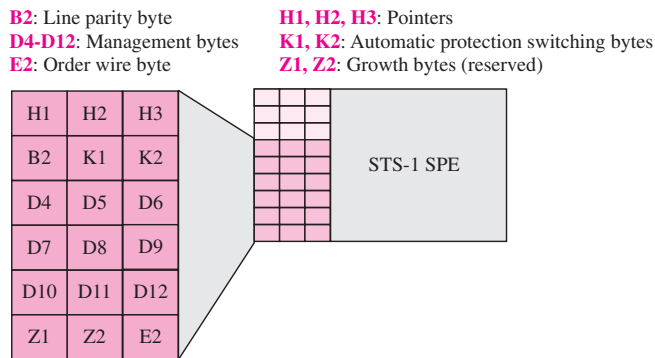
❑ **User's byte (F1).** The F1 bytes in consecutive frames form a 64-kbps channel that is reserved for user needs at the section level.

> **Section overhead is recalculated for each SONET device (regenerators and multiplexers).**

Line Overhead

Line overhead consists of 18 bytes. The labels, functions, and arrangement of these bytes are shown in Figure 17.8.

Figure 17.8   *STS-1 frame: line overhead*

B2: Line parity byte
D4-D12: Management bytes
E2: Order wire byte

H1, H2, H3: Pointers
K1, K2: Automatic protection switching bytes
Z1, Z2: Growth bytes (reserved)

H1	H2	H3
B2	K1	K2
D4	D5	D6
D7	D8	D9
D10	D11	D12
Z1	Z2	E2

STS-1 SPE

❑ **Line parity byte (B2).** Byte B2 is for bit interleaved parity. It is for error checking of the frame over a line (between two multiplexers). In an STS-*n* frame, B2 is calculated for all bytes in the previous STS-1 frame and inserted at the B2 byte for that frame. In other words, in a STS-3 frame, there are three B2 bytes, each calculated for one STS-1 frame. Contrast this byte with B1 in the section overhead.

❑ **Data communication channel bytes (D4 to D12).** The line overhead D bytes (D4 to D12) in consecutive frames form a 576-kbps channel that provides the same service as the D1–D3 bytes (OA&M), but at the line rather than the section level (between multiplexers).

❑ **Order wire byte (E2).** The E2 bytes in consecutive frames form a 64-kbps channel that provides the same functions as the E1 order wire byte, but at the line level.

❑ **Pointer bytes (H1, H2, and H3).** Bytes H1, H2, and H3 are pointers. The first two bytes are used to show the offset of the SPE in the frame; the third is used for justification. We show the use of these bytes later.

❑ **Automatic protection switching bytes (K1 and K2).** The K1 and K2 bytes in consecutive frames form a 128-kbps channel used for automatic detection of problems in
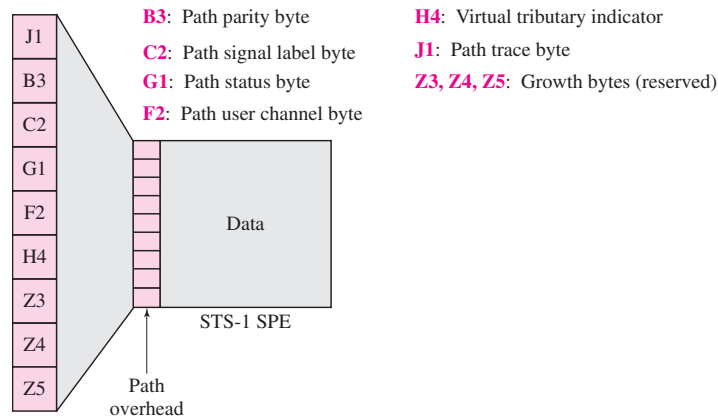
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line-terminating equipment. We discuss automatic protection switching (APS) later in the chapter.

❏ **Growth bytes (Z1 and Z2).** The Z1 and Z2 bytes are reserved for future use.

Synchronous Payload Envelope

The **synchronous payload envelope (SPE)** contains the user data and the overhead related to the user data (path overhead). One SPE does not necessarily fit it into one STS-1 frame; it may be split between two frames, as we will see shortly. This means that the path overhead, the leftmost column of an SPE, does not necessarily align with the section or line overhead. The path overhead must be added first to the user data to create an SPE, and then an SPE can be inserted into one or two frames. Path overhead consists of 9 bytes. The labels, functions, and arrangement of these bytes are shown in Figure 17.9.

Figure 17.9   *STS-1 frame: path overhead*

B3: Path parity byte
C2: Path signal label byte
G1: Path status byte
F2: Path user channel byte

H4: Virtual tributary indicator
J1: Path trace byte
Z3, Z4, Z5: Growth bytes (reserved)

STS-1 SPE

Data

Path overhead

❏ **Path parity byte (B3).** Byte B3 is for bit interleaved parity, like bytes B1 and B2, but calculated over SPE bits. It is actually calculated over the previous SPE in the stream.

❏ **Path signal label byte (C2).** Byte C2 is the path identification byte. It is used to identify different protocols used at higher levels (such as IP or ATM) whose data are being carried in the SPE.

❏ **Path user channel byte (F2).** The F2 bytes in consecutive frames, like the F1 bytes, form a 64-kbps channel that is reserved for user needs, but at the path level.

❏ **Path status byte (G1).** Byte G1 is sent by the receiver to communicate its status to the sender. It is sent on the reverse channel when the communication is duplex. We will see its use in the linear or ring networks later in the chapter.

❏ **Multiframe indicator (H4).** Byte H4 is the multiframe indicator. It indicates payloads that cannot fit into a single frame. For example, virtual tributaries can be

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combined to form a frame that is larger than an SPE frame and need to be divided into different frames. Virtual tributaries are discussed in the next section.

❏ **Path trace byte (J1).** The J1 bytes in consecutive frames form a 64-kbps channel used for tracking the path. The J1 byte sends a continuous 64-byte string to verify the connection. The choice of the string is left to the application program. The receiver compares each pattern with the previous one to ensure nothing is wrong with the communication at the path layer.

❏ **Growth bytes (Z3, Z4, and Z5).** Bytes Z3, Z4, and Z5 are reserved for future use.

**Path overhead is only calculated for end-to-end
(at STS multiplexers).**

Overhead Summary

Table 17.2 compares and summarizes the overheads used in a section, line, and path.

Table 17.2 *SONET/SDH rates*

Byte Function	Section	Line	Path
Alignment	A1, A2		
Parity	B1	B2	B3
Identifier	C1		C2
OA&M	D1–D3	D4–D12	
Order wire	E1		
User	F1		F2
Status			G1
Pointers		H1– H3	H4
Trace			J1
Failure tolerance		K1, K2	
Growth (reserved for future)		Z1, Z2	Z3–Z5

Example 17.4

What is the user data rate of an STS-1 frame (without considering the overheads)?

Solution
The user data part in an STS-1 frame is made of 9 rows and 86 columns. So we have

$$\text{STS-1 user data rate} = 8000 \times 9 \times (1 \times 86) \times 8 = 49.536 \text{ Mbps}$$
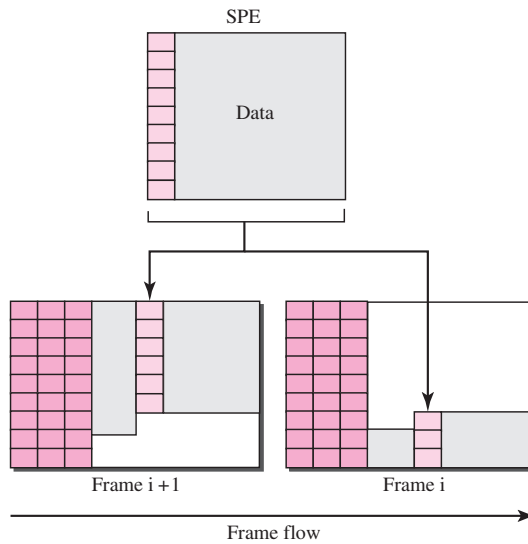
Encapsulation

The previous discussion reveals that an SPE needs to be encapsulated in an STS-1 frame. Encapsulation may create two problems that are handled elegantly by SONET using pointers (H1 to H3). We discuss the use of these bytes in this section.
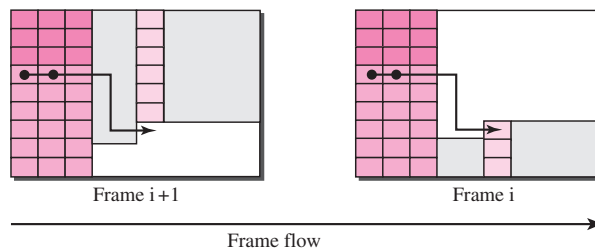
Offsetting

SONET allows one SPE to span two frames, part of the SPE is in the first frame and part is in the second. This may happen when one SPE that is to be encapsulated is not aligned time-wise with the passing synchronized frames. Figure 17.10 shows this situation. SPE bytes are divided between the two frames. The first set of bytes is encapsulated in the first frame; the second set is encapsulated in the second frame. The figure also shows the path overhead, which is aligned with the section/line overhead of any frame. The question is, How does the SONET multiplexer know where the SPE starts or ends in the frame? The solution is the use of pointers H1 and H2 to define the beginning of the SPE; the end can be found because each SPE has a fixed number of bytes. SONET allows the offsetting of an SPE with respect to an STS-1 frame.

Figure 17.10   *Offsetting of SPE related to frame boundary*

To find the beginning of each SPE in a frame, we need two pointers H1 and H2 in the line overhead. Note that these pointers are located in the line overhead because the encapsulation occurs at a multiplexer. Figure 17.11 shows how these 2 bytes point to

Figure 17.11   *The use of H1 and H2 pointers to show the start of an SPE in a frame*

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the beginning of the SPEs. Note that we need 2 bytes to define the position of a byte in a frame; a frame has 810 bytes, which cannot be defined using 1 byte.

Example 17.5

What are the values of H1 and H2 if an SPE starts at byte number 650?

Solution

The number 650 can be expressed in four hexadecimal digits as 0x028A. This means the value of H1 is 0x02 and the value of H2 is 0x8A.

Justification

Now suppose the transmission rate of the payload is just slightly different from the transmission rate of SONET. First, assume that the rate of the payload is higher. This means that occasionally there is 1 extra byte that cannot fit in the frame. In this case, SONET allows this extra byte to be inserted in the H3 byte. Now, assume that the rate of the payload is lower. This means that occasionally 1 byte needs to be left empty in the frame. SONET allows this byte to be the byte after the H3 byte.

17.4   STS MULTIPLEXING

In SONET, frames of lower rate can be synchronously time-division multiplexed into a higher-rate frame. For example, three STS-1 signals (channels) can be combined into one STS-3 signal (channel), four STS-3s can be multiplexed into one STS-12, and so on, as shown in Figure 17.12.

Figure 17.12   *STS multiplexing/demultiplexing*
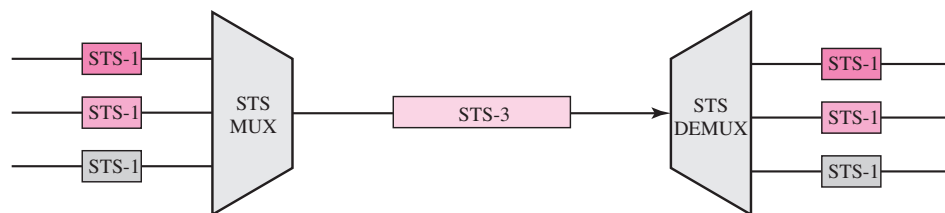
Multiplexing is synchronous TDM, and all clocks in the network are locked to a master clock to achieve synchronization.

In SONET, all clocks in the network are locked to a master clock.

We need to mention that multiplexing can also take place at the higher data rates. For example, four STS-3 signals can be multiplexed into an STS-12 signal. However, the STS-3 signals need to first be demultiplexed into 12 STS-1 signals, and then these

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twelve signals need to be multiplexed into an STS-12 signal. The reason for this extra
work will be clear after our discussion on byte interleaving.

Byte Interleaving

Synchronous TDM multiplexing in SONET is achieved by using **byte interleaving.**
For example, when three STS-1 signals are multliplexed into one STS-3 signal, each
set of 3 bytes in the STS-3 signal is associated with 1 byte from each STS-1 signal. Fig-
ure 17.13 shows the interleaving.
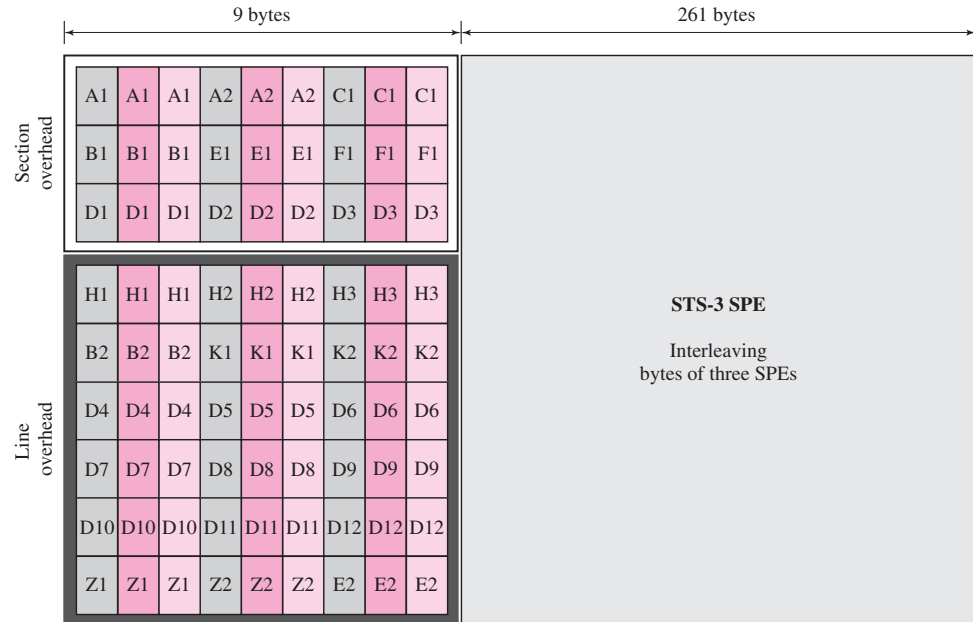
Figure 17.13   *Byte interleaving*
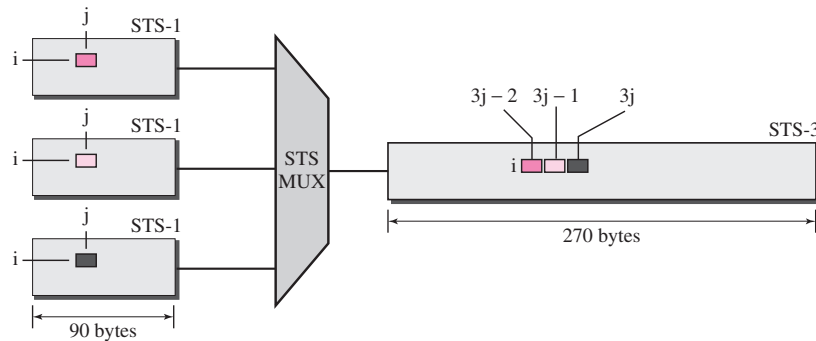
Note that a byte in an STS-1 frame keeps its row position, but it is moved into a
different column. The reason is that while all signal frames have the same number of
rows (9), the number of columns changes. The number of columns in an STS-n signal
frame is n times the number of columns in an STS-1 frame. One STS-n row, therefore,
can accommodate all n rows in the STS-1 frames.

Byte interleaving also preserves the corresponding section and line overhead as
shown in Figure 17.14. As the figure shows, the section overheads from three STS-1
frames are interleaved together to create a section overhead for an STS-1 frame. The
same is true for the line overheads. Each channel, however, keeps the corresponding bytes
that are used to control that channel. In other words, the sections and lines keep their own
control bytes for each multiplexed channel. This interesting feature will allow the use of
add/drop multiplexers, as discussed shortly. As the figure shows, there are three A1 bytes,
one belonging to each of the three multiplexed signals. There are also three A2 bytes,
three B1 bytes, and so on.

Demultiplexing here is easier than in the statistical TDM we discussed in Chapter 6
because the demultiplexer, with no regard to the function of the bytes, removes the first A1
and assigns it to the first STS-1, removes the second A1, and assigns it to second STS-1,
and removes the third A1 and assigns it to the third STS-1. In other words, the demulti-
plexer deals only with the position of the byte, not its function.

What we said about the section and line overheads does not exactly apply to the path
overhead. This is because the path overhead is part of the SPE that may have splitted into
two STS-1 frames. The byte interleaving, however, is the same for the data section of SPEs.

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Figure 17.14 *An STS-3 frame*

The byte interleaving process makes the multiplexing at higher data rates a little bit more complex. How can we multiplex four STS-3 signals into one STS-12 signal? This can be done in two steps: First, the STS-3 signals must be demultiplexed to create 12 STS-1 signals. The 12 STS-1 signals are then multiplexed to create an STS-12 signal.

Concatenated Signal

In normal operation of the SONET, an STS-*n* signal is made of *n* multiplexed STS-1 signals. Sometimes, we have a signal with a data rate higher than what an STS-1 can carry. In this case, SONET allows us to create an STS-*n* signal which is not considered as *n* STS-1 signals; it is one STS-*n* signal (channel) that cannot be demultiplexed into *n* STS-1 signals. To specify that the signal cannot be demultiplexed, the suffix *c* (for concatenated) is added to the name of the signal. For example, STS-3c is a signal that cannot be demultiplexed into three STS-1 signals. However, we need to know that the whole payload in an STS-3c signal is one SPE, which means that we have only one column (9 bytes) of path overhead. The used data in this case occupy 260 columns, as shown in Figure 17.15.

Concatenated Signals Carrying ATM Cells

We will discuss ATM and ATM cells in Chapter 18. An ATM network is a cell network in which each cell has a fixed size of 53 bytes. The SPE of an STS-3c signal can be a carrier of ATM cells. The SPE of an STS-3c can carry $9 \times 260 = 2340$ bytes, which can accommodate approximately 44 ATM cells, each of 53 bytes.
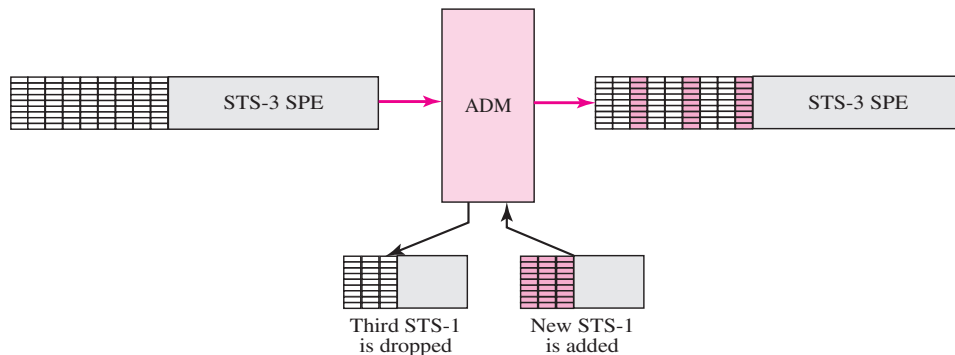
Figure 17.15   *A concatenated STS-3c signal*
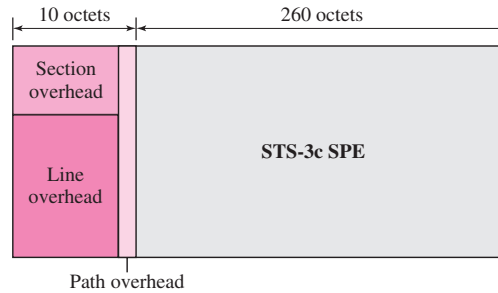
An STS-3c signal can carry 44 ATM cells as its SPE.

Add/Drop Multiplexer

Multiplexing of several STS-1 signals into an STS-*n* signal is done at the STS multiplexer (at the path layer). Demultiplexing of an STS-*n* signal into STS-1 components is done at the STS demultiplexer. In between, however, SONET uses add/drop multiplexers that can replace a signal with another one. We need to know that this is not demultiplexing/multiplexing in the conventional sense. An add/drop multiplexer operates at the line layer. An add/drop multiplexer does not create section, line, or path overhead. It almost acts as a switch; it removes one STS-1 signal and adds another one. The type of signal at the input and output of an add/drop multiplexer is the same (both STS-3 or both STS-12, for example). The add/drop multiplexer (ADM) only removes the corresponding bytes and replaces them with the new bytes (including the bytes in the section and line overhead). Figure 17.16 shows the operation of an ADM.

Figure 17.16   *Dropping and adding STS-1 frames in an add/drop multiplexer*

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17.5   SONET NETWORKS

Using SONET equipment, we can create a SONET network that can be used as a high-speed backbone carrying loads from other networks such as ATM (Chapter 18) or IP (Chapter 20). We can roughly divide SONET networks into three categories: linear, ring, and mesh networks, as shown in Figure 17.17.

**Figure 17.17**   *Taxonomy of SONET networks*
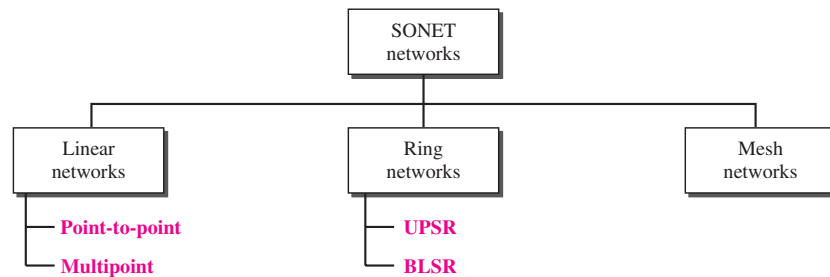
Linear Networks

A linear SONET network can be point-to-point or multipoint.

Point-to-Point Network

A point-to-point network is normally made of an STS multiplexer, an STS demultiplexer, and zero or more regenerators with no add/drop multiplexers, as shown in Figure 17.18. The signal flow can be unidirectional or bidirectional, although Figure 17.18 shows only unidirectional for simplicity.
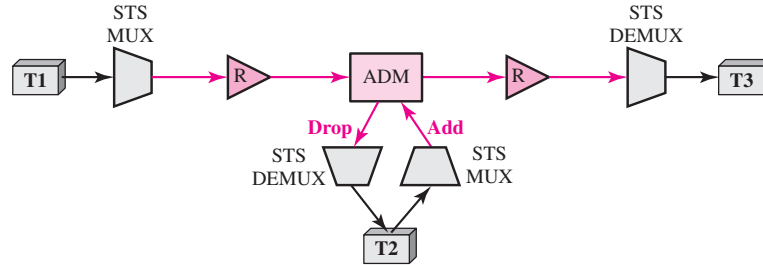
Figure 17.18   *A point-to-point SONET network*
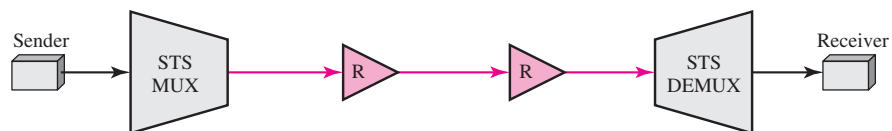
Multipoint Network

A multipoint network uses ADMs to allow the communications between several terminals. An ADM removes the signal belonging to the terminal connected to it and adds the signal transmitted from another terminal. Each terminal can send data to one or more downstream terminals. Figure 17.19 shows a unidirectional scheme in which each terminal can send data only to the downstream terminals, but the a multipoint network can be bidirectional, too.

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**Figure 17.19**   *A multipoint SONET network*

In Figure 17.19, T1 can send data to T2 and T3 simultaneously. T2, however, can send data only to T3. The figure shows a very simple configuration; in normal situations, we have more ADMs and more terminals.

Automatic Protection Switching

To create protection against failure in linear networks, SONET defines **automatic protection switching (APS).** APS in linear networks is defined at the line layer, which means the protection is between two ADMs or a pair of STS multiplexer/demultiplexers. The idea is to provide redundancy; a redundant line (fiber) can be used in case of failure in the main one. The main line is referred to as the work line and the redundant line as the protection line. Three schemes are common for protection in linear channels: one-plus-one, one-to-one, and one-to-many. Figure 17.20 shows all three schemes.

Figure 17.20   *Automatic protection switching in linear networks*
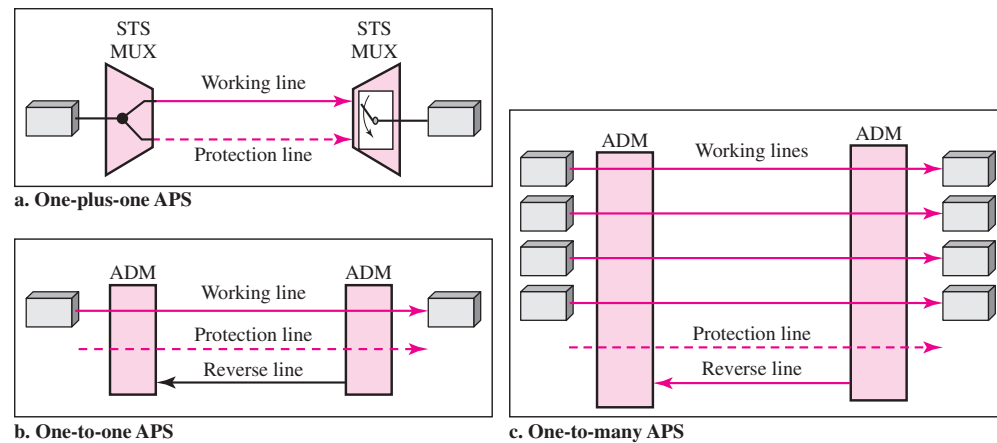
One-Plus-One APS   In this scheme, there are normally two lines: one working line and one protection line. Both lines are active all the time. The sending multiplexer

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sends the same data on both lines; the receiver multiplexer monitors the line and chooses the one with the better quality. If one of the lines fails, it loses its signal, and, of course, the other line is selected at the receiver. Although, the failure recovery for this scheme is instantaneous, the scheme is inefficient because two times the bandwidth is required. Note that one-plus-one switching is done at the path layer.

One-to-One APS   In this scheme, which looks like the one-plus-one scheme, there is also one working line and one protection line. However, the data are normally sent on the working line until it fails. At this time, the receiver, using the reverse channel, informs the sender to use the protection line instead. Obviously, the failure recovery is slower than that of the one-plus-scheme, but this scheme is more efficient because the protection line can be used for data transfer when it is not used to replace the working line. Note that the one-to-one switching is done at the line layer.

One-to-Many APS   This scheme is similar to the one-to-one scheme except that there is only one protection line for many working lines. When a failure occurs in one of the working lines, the protection line takes control until the failed line is repaired. It is not as secure as the one-to-one scheme because if more than one working line fails at the same time, the protection line can replace only one of them. Note that one-to-many APS is done at the line layer.

Ring Networks

ADMs make it possible to have SONET ring networks. SONET rings can be used in either a unidirectional or a bidirectional configuration. In each case, we can add extra rings to make the network self-healing, capable of self-recovery from line failure.

### Unidirectional Path Switching Ring

A **unidirectional path switching ring (UPSR)** is a unidirectional network with two rings: one ring used as the working ring and the other as the protection ring. The idea is similar to the one-plus-one APS scheme we discussed in a linear network. The same signal flows through both rings, one clockwise and the other counterclockwise. It is called UPSR because monitoring is done at the path layer. A node receives two copies of the electrical signals at the path layer, compares them, and chooses the one with the better quality. If part of a ring between two ADMs fails, the other ring still can guarantee the continuation of data flow. UPSR, like the one-plus-one scheme, has fast failure recovery, but it is not efficient because we need to have two rings that do the job of one. Half of the bandwidth is wasted. Figure 17.21 shows a UPSR network.

   Although we have chosen one sender and three receivers in the figure, there can be many other configurations. The sender uses a two-way connection to send data to both rings simultaneously; the receiver uses selecting switches to select the ring with better signal quality. We have used one STS multiplexer and three STS demultiplexers to emphasize that nodes operate on the path layer.

Bidirectional Line Switching Ring

Another alternative in a SONET ring network is **bidirectional line switching ring (BLSR)**. In this case, communication is bidirectional, which means that we need

Figure 17.21 *A unidirectional path switching ring*
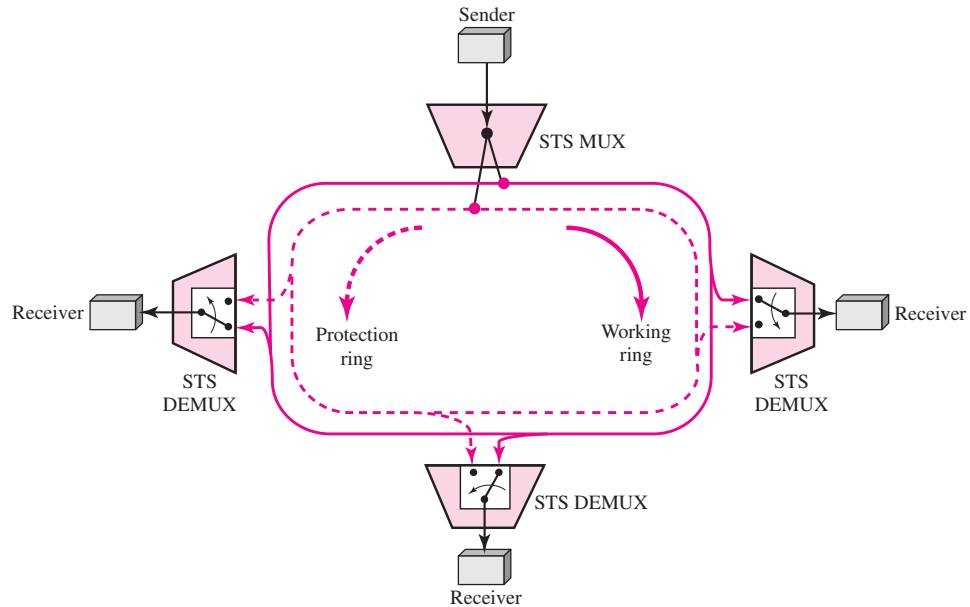
two rings for working lines. We also need two rings for protection lines. This means BLSR uses four rings. The operation, however, is similar to the one-to-one APS scheme. If a working ring in one direction between two nodes fails, the receiving node can use the reverse ring to inform the upstream node in the failed direction to use the protection ring. The network can recover in several different failure situations that we do not discuss here. Note that the discovery of a failure in BLSR is at the line layer, not the path layer. The ADMs find the failure and inform the adjacent nodes to use the protection rings. Figure 17.22 shows a BLSR ring.

Combination of Rings

SONET networks today use a combination of interconnected rings to create services in a wide area. For example, a SONET network may have a regional ring, several local rings, and many site rings to give services to a wide area. These rings can be UPSR, BLSR, or a combination of both. Figure 17.23 shows the idea of such a wide-area ring network.

Mesh Networks

One problem with ring networks is the lack of scalability. When the traffic in a ring increases, we need to upgrade not only the lines, but also the ADMs. In this situation, a mesh network with switches probably give better performance. A switch in a network mesh is called a cross-connect. A cross-connect, like other switches we have seen, has input and output ports. In an input port, the switch takes an OC-*n* signal, changes it to an STS-*n* signal, demultiplexes it into the corresponding STS-1 signals, and sends each

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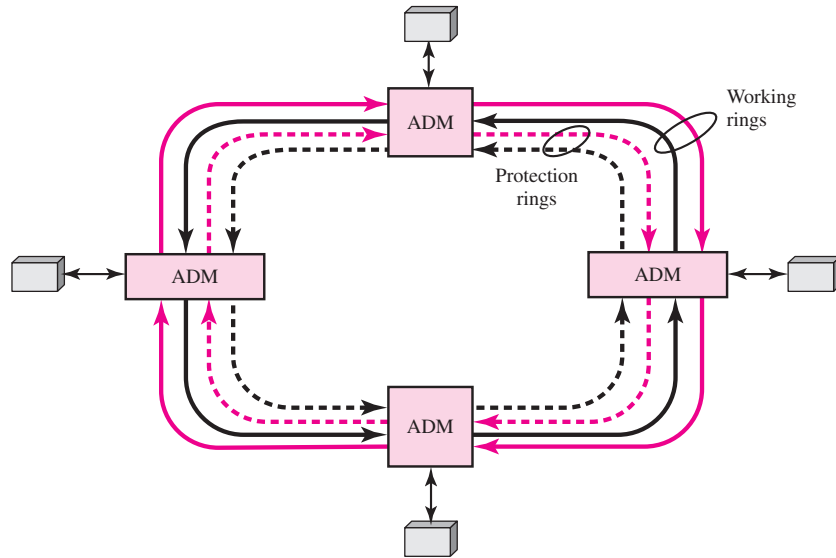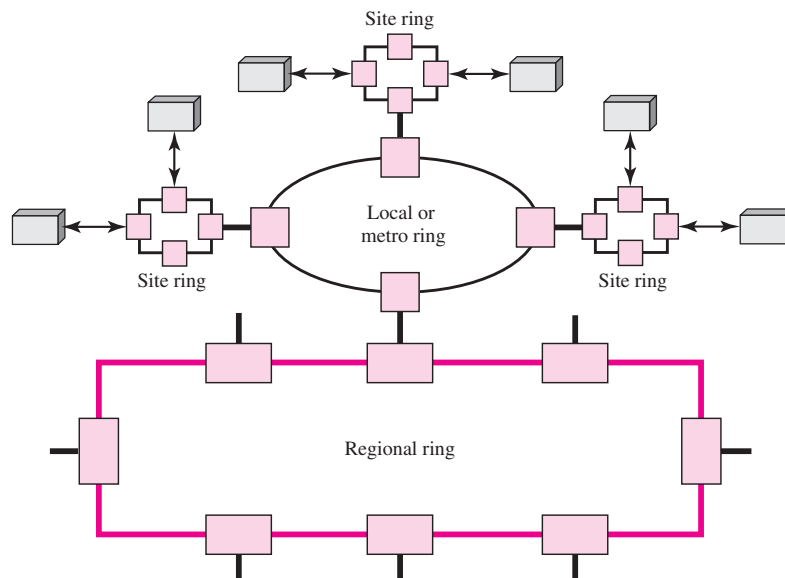**Figure 17.22**   *A bidirectional line switching ring*


Figure 17.23   *A combination of rings in a SONET network*

STS-1 signal to the appropriate output port. An output port takes STS-1 signals coming
from different input ports, multiplexes them into an STS-*n* signal, and makes an OC-*n*
signal for transmission. Figure 17.24 shows a mesh SONET network, and the structure of a
switch.

Figure 17.24   *A mesh SONET network*

a. SONET mesh network   b. Cross-connect switch
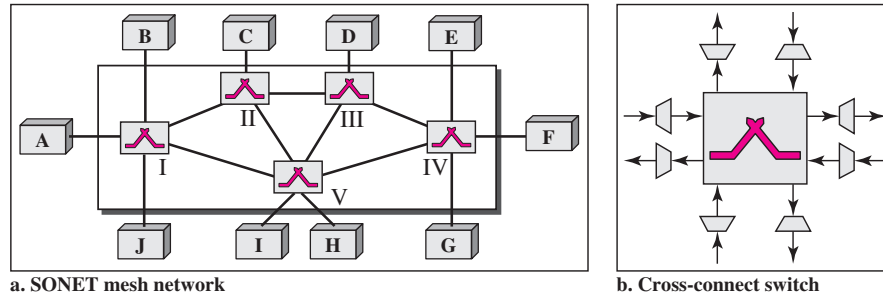
17.6   VIRTUAL TRIBUTARIES

SONET is designed to carry broadband payloads. Current digital hierarchy data rates (DS-1 to DS-3), however, are lower than STS-1. To make SONET backward-compatible with the current hierarchy, its frame design includes a system of **virtual tributaries (VTs)** (see Figure 17.25). A virtual tributary is a partial payload that can be inserted into an STS-1 and combined with other partial payloads to fill out the frame. Instead of using all 86 payload columns of an STS-1 frame for data from one source, we can subdivide the SPE and call each component a VT.

Figure 17.25   *Virtual tributaries*
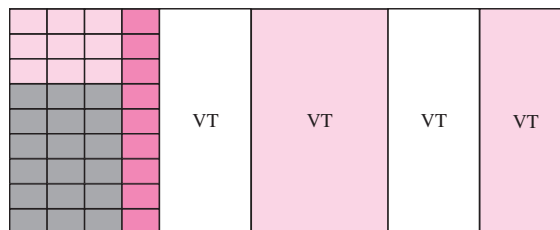
Types of VTs

Four types of VTs have been defined to accommodate existing digital hierarchies (see Figure 17.26). Notice that the number of columns allowed for each type of VT can be determined by doubling the type identification number (VT1.5 gets three columns, VT2 gets four columns, etc.).

❏   **VT1.5** accommodates the U.S. DS-1 service (1.544 Mbps).
❏   **VT2** accommodates the European CEPT-1 service (2.048 Mbps).
❏   **VT3** accommodates the DS-1C service (fractional DS-1, 3.152 Mbps).
❏   **VT6** accommodates the DS-2 service (6.312 Mbps).

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Figure 17.26 *Virtual tributary types*

```
VT1.5 = 8000 frames/s   3 columns   9 rows  8 bits = 1.728 Mbps
VT2   = 8000 frames/s   4 columns   9 rows  8 bits = 2.304 Mbps
VT3   = 8000 frames/s   6 columns   9 rows  8 bits = 3.456 Mbps
VT6   = 8000 frames/s  12 columns   9 rows  8 bits = 6.912 Mbps
```

VT1.5   VT2   VT3   VT6
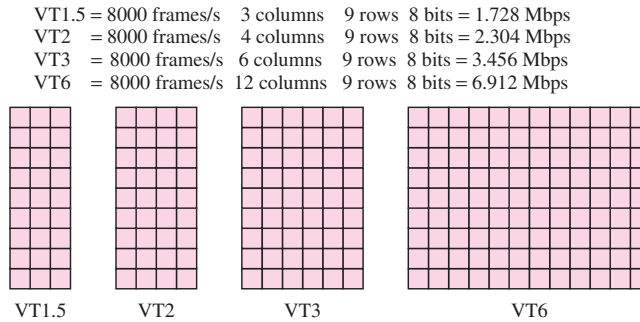
When two or more tributaries are inserted into a single STS-1 frame, they are interleaved column by column. SONET provides mechanisms for identifying each VT and separating them without demultiplexing the entire stream. Discussion of these mechanisms and the control issues behind them is beyond the scope of this book.

17.7   RECOMMENDED READING

For more details about subjects discussed in this chapter, we recommend the following books. The items in brackets [. . .] refer to the reference list at the end of the text.

Books

SONET is discussed in Section 2.5 of [Tan03], Section 15.2 of [Kes97], Sections 4.2 and 4.3 of [GW04], Section 8.2 of [Sta04], and Section 5.2 of [WV00].

17.8   KEY TERMS

add/drop multiplexer (ADM)	path overhead (POH)
automatic protection switching (APS)	photonic layer
bidirectional line switching ring (BLSR)	regenerator
byte interleaving	section
line	section layer
line layer	section overhead (SOH)
line overhead (LOH)	STS demultiplexer
optical carrier (OC)	STS multiplexer
path	Synchronous Digital Hierarchy (SDH)
path layer	Synchronous Optical Network (SONET)

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synchronous payload envelope (SPE)	terminal
synchronous transport module (STM)	unidirectional path switching ring (UPSR)
synchronous transport signal (STS)	virtual tributary (VT)

17.9   SUMMARY

❏ Synchronous Optical Network (SONET) is a standard developed by ANSI for fiber-optic networks: Synchronous Digital Hierarchy (SDH) is a similar standard developed by ITU-T.

❏ SONET has defined a hierarchy of signals called synchronous transport signals (STSs). SDH has defined a similar hierarchy of signals called synchronous transfer modules (STMs).

❏ An OC-*n* signal is the optical modulation of an STS-*n* (or STM-*n*) signal.

❏ SONET defines four layers: path, line, section, and photonic.

❏ SONET is a synchronous TDM system in which all clocks are locked to a master clock.

❏ A SONET system can use the following equipment:
  1. STS multiplexers
  2. STS demultiplexers
  3. Regenerators
  4. Add/drop multiplexers
  5. Terminals

❏ SONET sends 8000 frames per second; each frame lasts 125 μs.

❏ An STS-1 frame is made of 9 rows and 90 columns; an STS-*n* frame is made of 9 rows and $n \times 90$ columns.

❏ STSs can be multiplexed to get a new STS with a higher data rate.

❏ SONET network topologies can be linear, ring, or mesh.

❏ A linear SONET network can be either point-to-point or multipoint.

❏ A ring SONET network can be unidirectional or bidirectional.

❏ To make SONET backward-compatible with the current hierarchy, its frame design includes a system of virtual tributaries (VTs).

17.10   PRACTICE SET

Review Questions

1. What is the relationship between SONET and SDH?
2. What is the relationship between STS and STM?
3. How is an STS multiplexer different from an add/drop multiplexer since both can add signals together?

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4. What is the relationship between STS signals and OC signals?
5. What is the purpose of the pointer in the line overhead?
6. Why is SONET called a synchronous network?
7. What is the function of a SONET regenerator?
8. What are the four SONET layers?
9. Discuss the functions of each SONET layer.
10. What is a virtual tributary?

Exercises

11. What are the user data rates of STS-3, STS-9, and STS-12?
12. Show how STS-9's can be multiplexed to create an STS-36. Is there any extra overhead involved in this type of multiplexing?
13. A stream of data is being carried by STS-1 frames. If the data rate of the stream is 49.540 Mbps, how many STS-1 frames per second must let their H3 bytes carry data?
14. A stream of data is being carried by STS-1 frames. If the data rate of the stream is 49.530 Mbps, how many frames per second should leave one empty byte after the H3 byte?
15. Table 17.2 shows that the overhead bytes can be categorized as A, B, C, D, E, F, G, H, J, K, and Z bytes.
    a. Why are there no A bytes in the LOH or POH?
    b. Why are there no C bytes in the LOH?
    c. Why are there no D bytes in the POH?
    d. Why are there no E bytes in the LOH or POH?
    e. Why are there no F bytes in the LOH or POH?
    f. Why are there no G bytes in the SOH or LOH?
    g. Why are there no H bytes in the SOH?
    h. Why are there no J bytes in the SOH or LOH?
    i. Why are there no K bytes in the SOH or POH?
    j. Why are there no Z bytes in the SOH?
16. Why are B bytes present in all three headers?