

# **SONET**

(Synchronous Optical Network)

18-756 Circuit Switching and Packet Switching

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## **Introduction**

SONET (Synchronous Optical Network) is a standard for optical data transport. It defines optical signals and a synchronous frame structure for multiplexed digital traffic. It is a major contender as the physical transport layer for the next decade. SONET is an International standard which has been adopted in the United States, Europe and in Japan. It provides necessary bandwidth for today's networks and can grow to accommodate the networks of the future. It provides advanced fault tolerance and survivability. The existing digital hierarchy in the United States suffered from a deficiency of overhead information to manage the network. SONET provides advanced OAM&P (Operations, Administration, Maintenance and Provisioning) features.

## Motivation

There is a growing trend towards using optical fiber media for data transport. Optical fiber has the following advantages over coaxial cable, twisted-pair and microwave networks.

- Optical fiber offers a much higher bandwidth
- Optical fiber can be carried over longer distances without repeaters (regenerators)
- Fiber is immune to interference
- Fiber is more secure. It is hard to tap and unwanted tapping can be detected
- Fiber is cheaper to maintain in the long run
- A small strand of fiber can offer enormous bandwidth. Fiber is also very light-weight
- Bandwidth upgrades can be made on the same fiber
- It has very low bit error rates (BER)

The existing North American Digital Hierarchy was created to carry digitized voice over twisted wire. Each level in the hierarchy is called a digital stream (DS). The lower level digital streams are multiplexed into the higher digital streams. The lowest level in the hierarchy is DS0 that carries a single voice channel.

<i>Stream Name</i>	<i>Bit Rate</i>	<i>Structure</i>	<i>Number of DS0s</i>
DS0	64 Kbps	1 voice channel	1
DS1	1.544 Mbps	24 x DS0	24
DS3	44.736 Mbps	28 x DS1	672

**Table 1. Digital Stream Data Rates**

The European and Japanese digital hierarchies are closely related to this structure. SONET is a recreation of the digital transmission hierarchy with a whole family of Optical Carriers (OC levels) running at speeds ranging from 51.84 Mbps in the US and 155.52 Mbps in Europe to about 9.9 Gbps. The existing digital multiplexing system is asynchronous at DS3 and lower levels. Asynchronous multiplexing uses multiple stages. For example, when DS0 signals are multiplexed into a DS1 stream extra bits (bit-stuffing) are added to account for variations in the individual streams. When the DS1 stream is multiplexed into a DS-3 stream, bit-stuffing is used again. At this level, it is not possible to recover the DS0 without first demultiplexing the DS1 signal and the demultiplexing the DS0 out of the demultiplexed DS1 signal. Asynchronous multiplexing adds a lot of overhead and requires a large number of multiplexers and digital cross connects.

SONET performs synchronous multiplexing at all levels. To effectively do this, it uses a concept called pointers for frame synchronization. Low level SONET streams can be extracted from a high level SONET stream synchronously. The SONET optical levels are shown in the table below.

OC-N level	Bit Rate (Mbps)	Number of DS0s	Number of DS1s	Number of DS3s
1	51.84	672	28	1
3	155.52	2016	84	3
6	311.04	4032	168	6
9	466.56	6048	252	9
12	622.08	8064	336	12
18	933.12	12096	504	18
24	1244.16	16128	672	24
36	1866.24	24192	1008	36
48	2488.32	32256	1344	48
96	4976.00	64512	2688	96
192	9952.00	129024	5376	192

**Table 2. SONET optical levels**

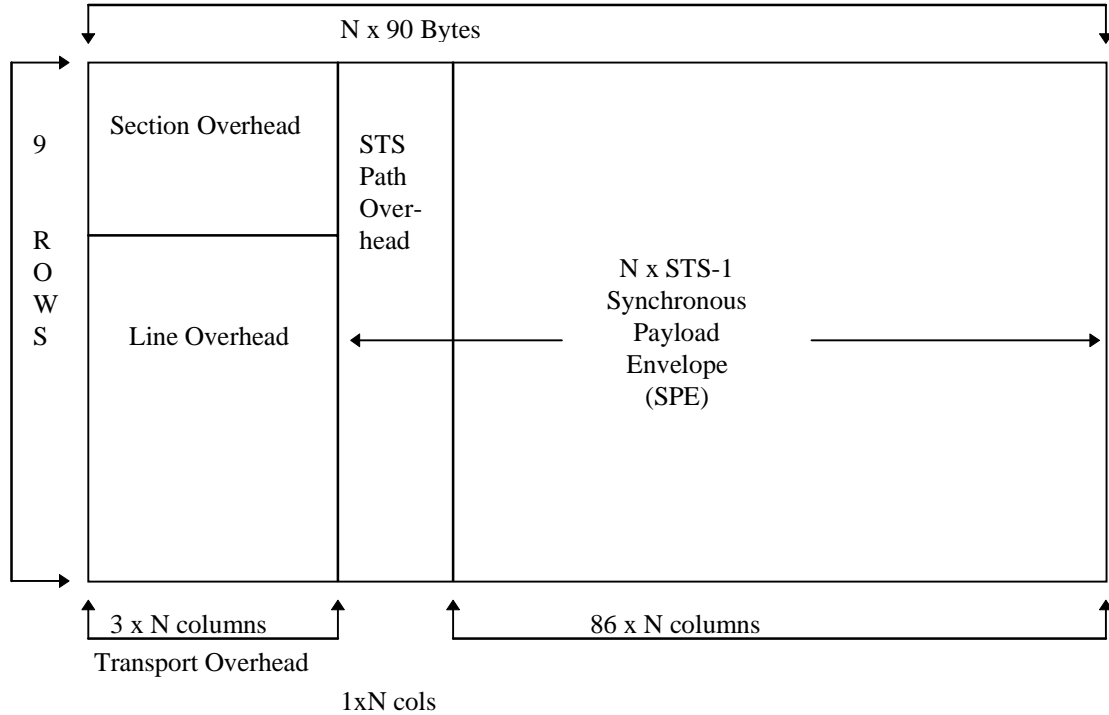
SONET can also carry signals at speeds lower than the OC-1 rate using Virtual Tributaries (VTs).

## **Synchronous vs. Asynchronous**

SONET stands for Synchronous Optical Network. Synchronous used in this context refers to the multiplexing method used to combine channels on SONET. Synchronous multiplexing in SONET is achieved by ensuring that all the input channels into the multiplexer have clocks that are synchronized to a certain level of tolerance. SONET uses byte-interleaved multiplexing at all levels. The control information to separate the channels is inserted into the channels before they are multiplexed. Other than this there is no other overhead. For example, an STS-3 (Synchronous Transport Signal level) / OC-3 channel is combined by multiplexing three STS-1/OC-1 channels. The Line Rate of an STS-1 channel is 51.84 Mbps and the line rate of an STS-3 channel is 155.52 Mbps which is exactly three times the input stream. Thus aggregating channels into higher levels add no additional overhead.

## SONET Frame Structure

A SONET STS-N frame format is shown below.



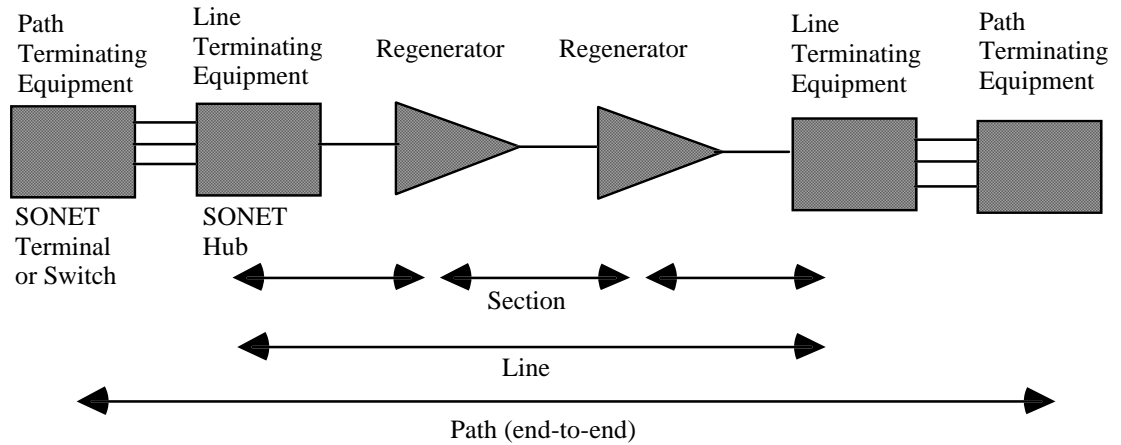
**Figure 1. SONET Frame Structure**

SONET defines optical carrier (OC) levels and electrically equivalent synchronous transport signals (STSs) for the transmission hierarchy. The base format of SONET is a synchronous STS-1 signal that operates at 51.84 Mbps. The format of the STS-1 SONET frame is shown in Figure 1.

An STS-1 frame has 90 columns and 9 rows which gives a frame size of 810 bytes. This equates to a basic STS-1 transfer rate of 51.84 Mb/s. The frame consists of two main areas: (1) transport overhead, which occupy the first three columns and (2) the synchronous payload envelope (SPE), which occupy the remaining 87 columns. The signal is transmitted byte-by-byte beginning with byte one, scanning left to right from row one to row nine. The entire frame is transmitted in 125 microseconds. Higher level signals (STS-N) are integer multiples of the base rate. STS-1 frames are interleaved and converted to optics to form OC-N signals.

## SONET Frame Overhead

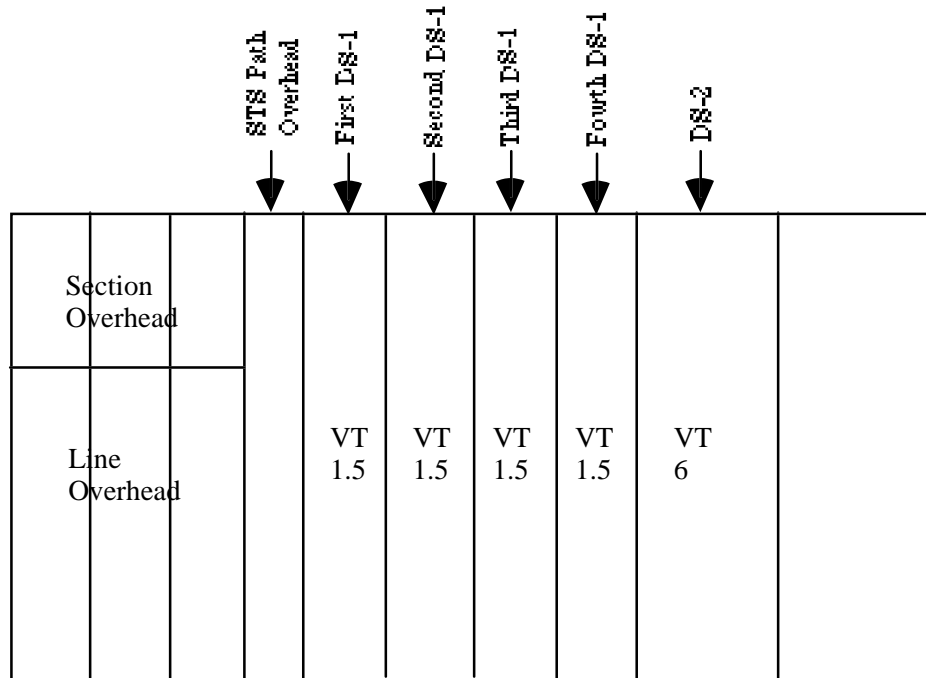
As stated above, SONET provides overhead information known as transport overhead in the first three columns of the STS-1 frame. As shown in Figure 1, the transport overhead is composed of section overhead and line overhead. Section overhead is used for communications between adjacent network elements. Line overhead is for the STS-N signal between the STS-N multiplexers. In addition to the transport overhead, SONET provides path-level overhead that is part of the SPE. Path-level overhead is carried from end-to-end; it is added to DS-1 signals when they are mapped into virtual tributaries (virtual tributaries are explained below) and for STS-1 payloads that travel end-to-end. Thus, SONET overhead uses a layered approach. Figure 2 shows the layering of the overhead.



**Figure 2. SONET Overhead Layers**

## Virtual Tributaries

SONET also defines synchronous signals known as virtual tributaries (VTs) to transport lower-speed transmission. VTs operate at sub-STS-1 levels. The four defined sizes of VTs are VT-1.5 (1.728 Mbps), VT-2 (2.304 Mbps), VT-3 (3.152 Mbps) and VT-6 (6.912 Mbps). Within an STS-1 frame, each VT occupies a number of columns as shown in Figure 3.



**Figure 3. VTs within a STS-1 frame**

Within the STS-1, virtual tributary groups can be mixed together to form an STS-1 payload. To accommodate different mixes of VTs in an efficient manner, the STS-1 SPE is divided into seven groups. A VT group may contain one VT-6, two VT-3s, three VT-2s, or four VT-1.5s. Although different types of VT groups may be mixed into one STS-1 SPE, a VT group must contain only one size of VTs. To synchronize the various low-speed signals to a common rate before multiplexing, bit stuffing is used.

## SONET and Other Data Streams and Protocols

The design of the frame and signaling for SONET makes it compatible with the traditional, existing networks. Most prominent of such networks is the telephone network. The frame format described above for STS-1 was chosen such that the 125 microseconds to transmit matches the standard telephony 64 kilobytes per second circuit. A single STS-1 payload is capable of carrying 672 voice channels. Table 3 shows a comparison of SONET with the existing digital signals and voice channels.

<i>SONET</i>	<i>Data Rate (Mbps)</i>	<i>DS-0s (64 kbps)</i>	<i>DS-1s (1.54 Mbps)</i>	<i>DS-3s (2.048 Mbps)</i>	<i>Voice Channels</i>
STS-1	51.84	672	28	1	672
STS-3	155.52	2016	84	3	2016
STS-9	466.56	6048	252	9	6048
STS-12	622.08	8064	336	12	8064
STS-18	933.12	12,096	504	18	12,096
STS-24	1244.16	16,128	672	24	16,128
STS-36	1866.24	24,192	1008	36	24,192
STS-48	2488.32	32,256	1344	48	32,256

**Table 3. Comparison of SONET and existing digital signals and voice channels.**

SONET also provides the necessary bandwidth to transport information from one Broadband Integrated Services Digital Network (BISDN) switch or terminal to another. BISDN can be used to handle voice, data and video. An H4 is a digital broadband signal of 150 Mbps used to carry high-definition TV signal. To provide a broadcast quality of such a signal, the signal may be transported by concatenating three STS-1 signals or by using a STS-3 (51.84 \* 3 Mbps) signal. Many of these broadband services may use Asynchronous Transfer Mode (ATM) -- a fast-packet-switching technique using short, fixed-length packets. Because of its bandwidth capacity, SONET is a logical carrier for ATM. ATM operates at 155 Mbps thus an STS-3 may be used to carry the signal. However, to provide better efficiency, ATM is usually carried in multiples of STS-12c.

SONET is also compatible with the European transmission hierarchy. SONET is considered to be a subset of Synchronous Digital Hierarchy (SDH), which is a world standard for synchronous transmission. SONET and SDH converge at SDH's base level of 155 Mbps which is equivalent to three STS-1 signals or a single STS-3 signal. Table 4 compares the transmission hierarchies of SONET and SDH.

Bit Rate (Mbps)	SONET	SDH
51.84	STS-1	-
155.52	STS-3	STM-1
622.08	STS-12	STM-4
1244.16	STS-24	-
2488.32	STS-48	STM-16
9953.28	STS-192	STM-64

**Table 4. Comparison of the transmission hierarchies of SONET and SDH.**

The major advantage of SONET is its ability to carry both synchronous transfer mode (STM) and asynchronous transfer mode (ATM) signals simultaneously. This allows SONET to provide a single transport backbone for all applications. A significant amount of SONET equipment has been installed in the network over the past five years to transport telephony signals. Now that ATM is being to be deployed, those same network elements can be used simultaneously to carry both the STM and ATM signals.

## **Add-Drop Multiplexing**

In existing networks when there is a need to extract /insert a lower-speed channel from/into a high-speed line, the lower-speed channels must be completely demultiplexed/multiplexed before being passed on. Multiplexing and demultiplexing can become very expensive as the number of low-speed channels that are used increases. SONET overcomes this problem through the use of Add/Drop Multiplexers (ADM). ADMs allow low-speed signals to be added or dropped without demultiplexing the entire signal through the use of synchronous multiplexing.

## SONET Frame Synchronization

SONET frames can be transported across different networks. For the SONET frames to be correctly passed between networks, it is essential that the clocks for both networks be perfectly synchronized. To maintain clock synchronization across networks, SONET maintains a clock hierarchy, much like the North American Digital Hierarchy. A network conforming to SONET standards must be able to derive its clock from a Stratum 3 or higher clock. Even with highly synchronized clocking mechanisms, there are chances for drift. SONET can operate between synchronous networks (all clocks in the system have the same clock) or plesiochronous networks (all clocks in the system have very nearly the same clock).

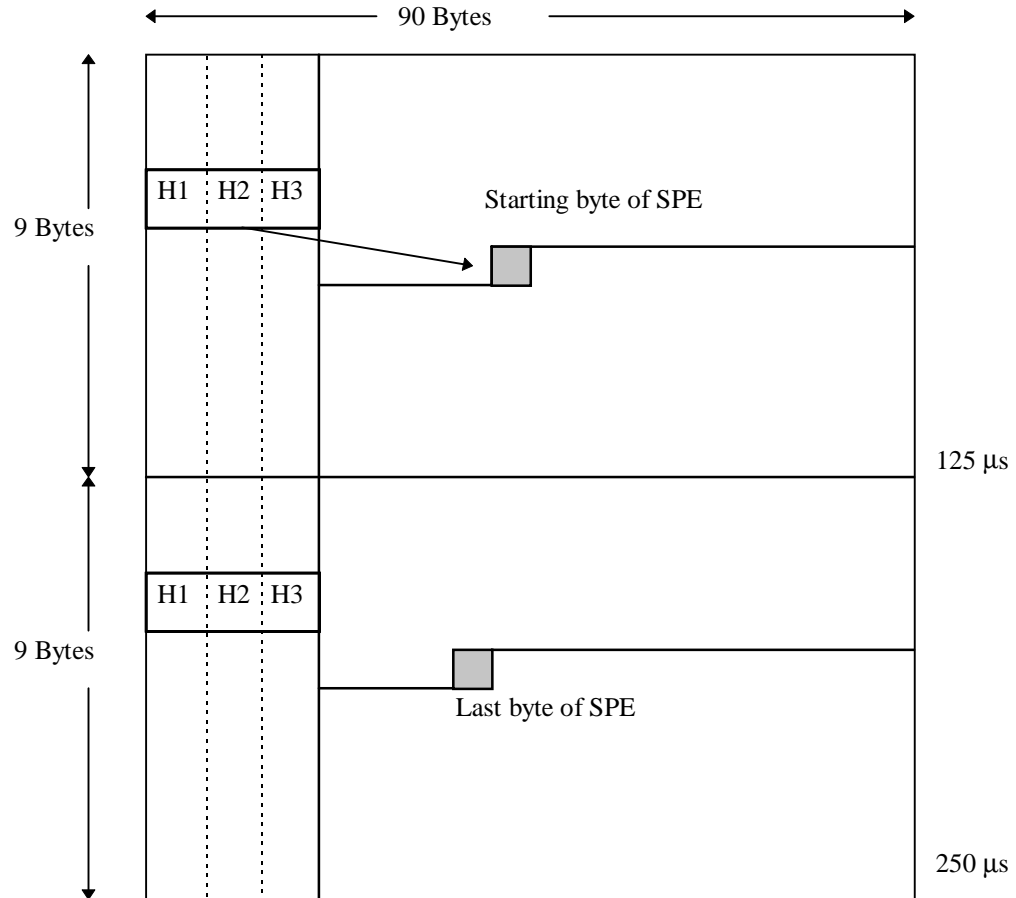
There are two common ways of dealing with data transfer in a non-synchronous environment. Of course, both these methods can only be used when the incoming stream (which we will call X. The payload is contained within X) has a lower rate than the SONET stream. One way to deal with this is to bit-stuff the incoming stream to match the available payload capacity. This method can accommodate large frequency variations. However, this is not always a good solution. If the SONET signal is multiplexed to a higher level, then extraction of the payload from the SONET signal involves first de-stuffing the bit-stuffed stream to get X and then extracting the needed payload from it. This is contrary to the rest of the SONET operation. One of the features that SONET prides itself on is the fact that extraction of a base signal from a high level multiplexed stream can be done without demultiplexing. Another commonly used solution is to assign each tributary a fixed location mapping in a higher-rate signal. This means that the tributary will only be found at certain locations in the SONET frame. In this case no de-stuffing is necessary to extract the needed tributary. Extraction of the payload can be done without de-multiplexing. Consider the case where the clocks of the tributary and the SONET stream are perfectly synchronized but are phase-shifted. Now to fit the tributary into the SONET stream, there has to be a buffer whose size has to be the size of the tributary that is carried within one frame. Since there is a SONET frame transmitted every 125 $\mu$ s, the tributary could potentially be delayed up to 125 $\mu$ s.

SONET uses a concept called “pointers” to deal with the frequency and phase differences in plesiochronous networks. The SONET overhead format is shown in Figure 4.

	Row 1	Row 2	Row 3	Path Layer Overhead This is part of the SONET payload
Section Overhead	Framing A1	Framing A2	STS-1 ID C1	Trace J1
	BIP-8 B1	Orderwire E1	User F1	BIP-8 B3
	Data Com D1	Data Com D2	Data Com D3	Signal Label C2
Line Overhead	Pointer H1	Pointer H2	Pointer Action H3	Path Status G1
	BIP-8 B2	APS K1	APS K2	User Channel F2
	Data Com D4	Data Com D5	Data Com D6	Multiframe H4
	Data Com D7	Data Com D8	Data Com D9	Growth Z3
	Data Com D10	Data Com D11	Data Com D12	Growth Z4
	Growth Z1	Growth Z2	Orderwire E2	Growth Z5

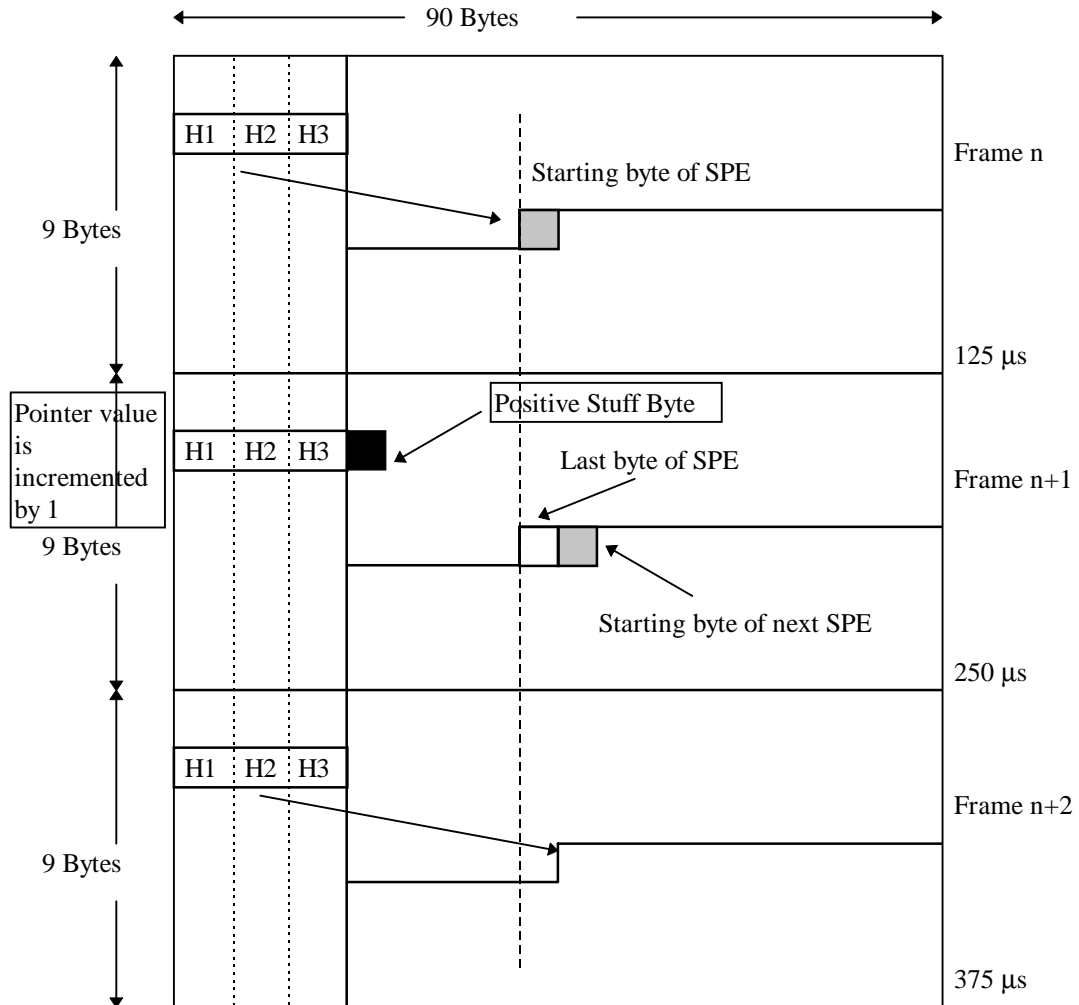
**Figure 4. SONET Overhead Format**

The H1 and H2 bytes in the STS-1 frame point to the starting byte in the SPE (Synchronous Payload Envelope). The Synchronous Payload Envelope includes the path overhead information. The SPE has a fixed size of 87 x 9 bytes in an STS-1 frame. The SPE is not fixed relative to the SONET frame. It can float around in the SONET frame. The following is an example of transport of the SPE in a SONET frame. As seen in Figure 5, the SPE need not start aligned with a frame. The size of the SPE is fixed at 87x 9 bytes (in STS-1).



**Figure 5. SPE in a SONET frame**

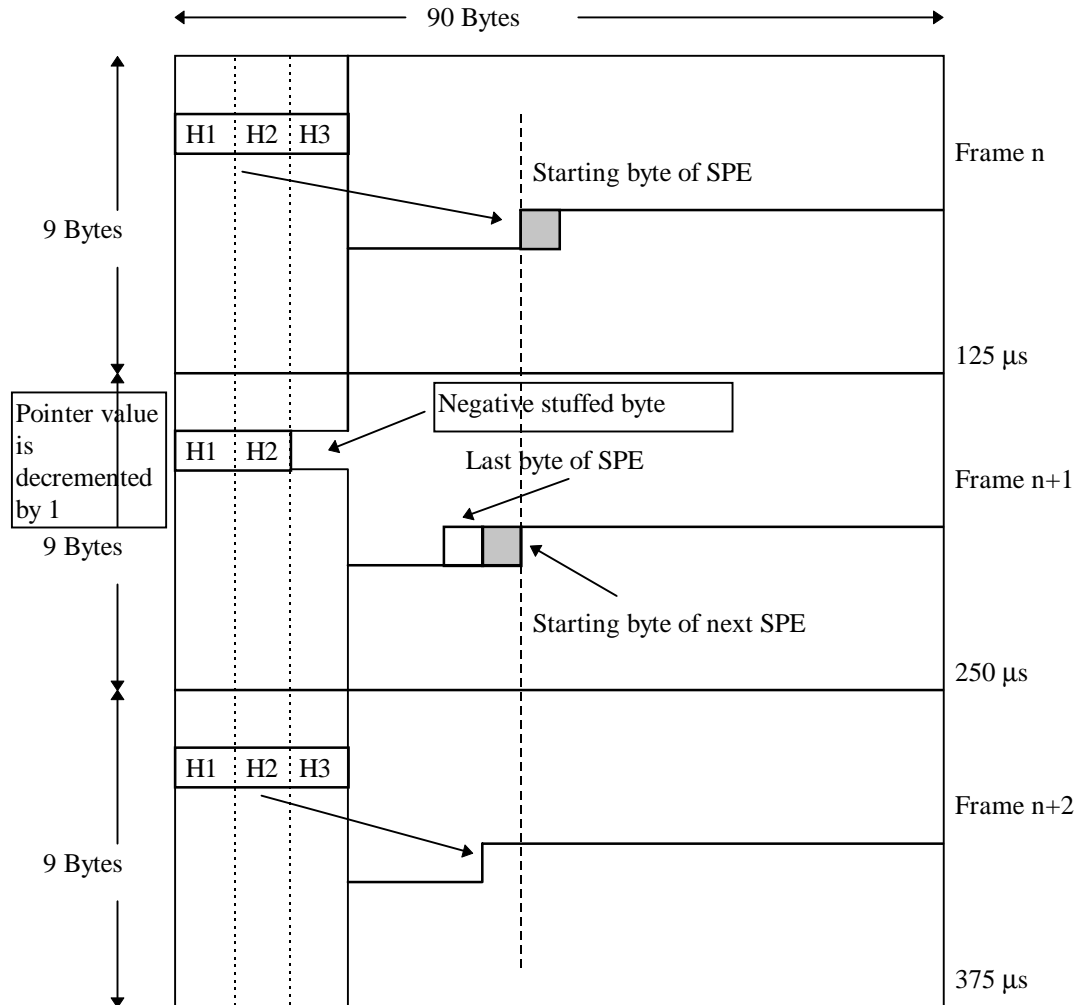
The pointer method used in SONET has obvious advantages over the conventional methods described before. The pointer method takes care of phase variations. However, simply using the pointer does not take care of frequency differences. The H3 byte in the SONET frame is used to take care of frequency differences. If the payload data rate is low with respect to the STS-1 frame rate, the byte following the H3 byte is stuffed (skipped) and the pointer (consisting of bytes H1 and H2) is incremented. This is called positive stuffing. A graphical description of positive stuffing in Figure 6.



**Figure 6. Positive Byte Stuffing**

As seen in Figure 6, the byte after the H3 byte is stuffed. This byte will be ignored. However, the size of the SPE has not changed. The effective result is that the SPE transmission time takes a longer duration. In this way, SONET can cater to a situation where the STS-1 payload data comes in at a slower rate than the STS-1 frame rate.

If the STS-1 payload data rate is high with respect to the STS-1 frame rate, the payload pointer is decremented by 1 and the H3 slot is filled with an extra byte of data. This is known as negative byte stuffing and is shown graphically Figure 7. The effective result is that one SPE worth of data is transmitted slightly faster than normal.



**Figure 7. Negative Byte Stuffing**

The positive or negative stuffing can be done only once every four frames (three frames following the frame in which the pointer adjustment occurs must have the same value). Therefore a byte adjustment can be made only once every four frames. Thus, SONET can tolerate a variation in data rates of  $\pm 16$  Kbps.

## **Fault Tolerance**

### ***Failure Monitoring***

SONET has extensive error monitoring and correction capability “built-in” to the line overhead to allow speedy detection of failures before they degrade to serious levels. SONET provides rapid fault isolation and end-to-end performance monitoring. Additionally, SONET network topology -- i.e., ring architecture -- plays a big part in correcting failures.

Several bytes in the SONET overhead are reserved for a method of error monitoring called Bit Interleave Parity-8 (BIP-8). BIP-8 creates an even parity over the bits in the transmitting signal. With this method of error monitoring, performance information is available for all levels of SONET line rates down to the Virtual Tributary (VT) rate.

### ***Fault Tolerance***

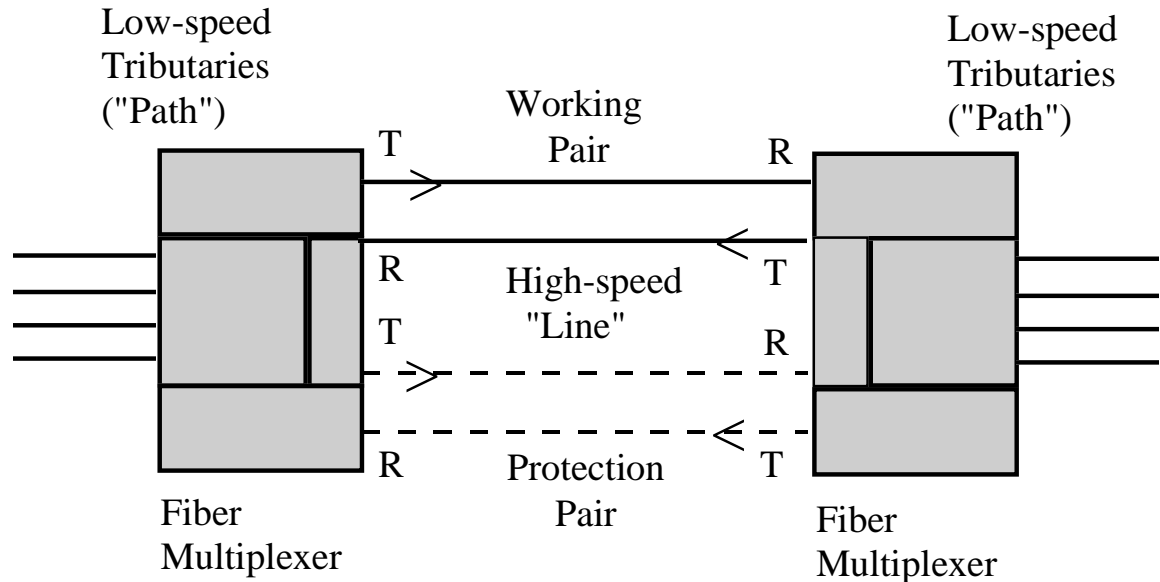
One of SONET's main advantages over current fiber optic transmission systems is a ring architecture. Moreover, SONET provides certain advantages over non-SONET ring architectures. SONET network topology can be organized into several types of rings, each of which provides for automatic network restoration -- or self-healing -- in the event of a network failure. Although the technology to take full advantage of SONET's many features are not yet mature, the survivability of SONET rings can be exploited today. Self-healing rings are implemented by combining two ideas: protection switching and uni- and bi-directional traffic transport.

### ***Protection Switching***

Protection switching is a backup technique used to support high volumes of network traffic over two fibers. There are two types of protection switching: line-protection switching and path-protection switching.

Line-protection switching, also known as 1:1 protection switching, is accomplished by duplicating the bi-directional line connection between two point-to-point fiber multiplexers. In this way, each point-to-point link is comprised of four fibers, two of which are used as the working transmit/receive pair, and two of which are the protection pair. If the working pair is disrupted or degraded, the signal loss is detected by both multiplexers, and traffic is then switched to the backup or protection pair. Although the line-protection method is used in conventional asynchronous systems, it is enhanced in SONET by using special instructions reserved in overhead. On the downside, line-protection switching is more expensive than non-protected systems because it requires four fibers -- and thus more electronics -- than simple two-fiber systems. Additionally, line switching occurs if just one channel degrades or fails. Thus

the other channels that were unaffected by the degradation are affected by the switch because *all* channels are switched to the protection pair and the overhead involved in executing the switch instructions is complex and time consuming.



**Figure 8. Line Switching**

Path-protection switching, also known as 1+1 protection switching, assumes that a problem with a fiber line is unlikely. In this technique, the traffic from the transmitting node is sent on both the working and the protection fiber pairs. The two copies of traffic that arrive at the receiver are compared, and only the best copy is used. Although this method is just as expensive in terms of fibers and electronics, it is more versatile and selective. If, for example, one channel on the working pair is degraded, the receiving node simply switches it out and replaces it with the good copy from the protection pair. The other channels remain completely unaffected. The versatility of path-switching is represented by the fact that both copies need not be transmitted over fiber. For example, one could be transmitted over a fiber system and the other could be transmitted over a wireless link.

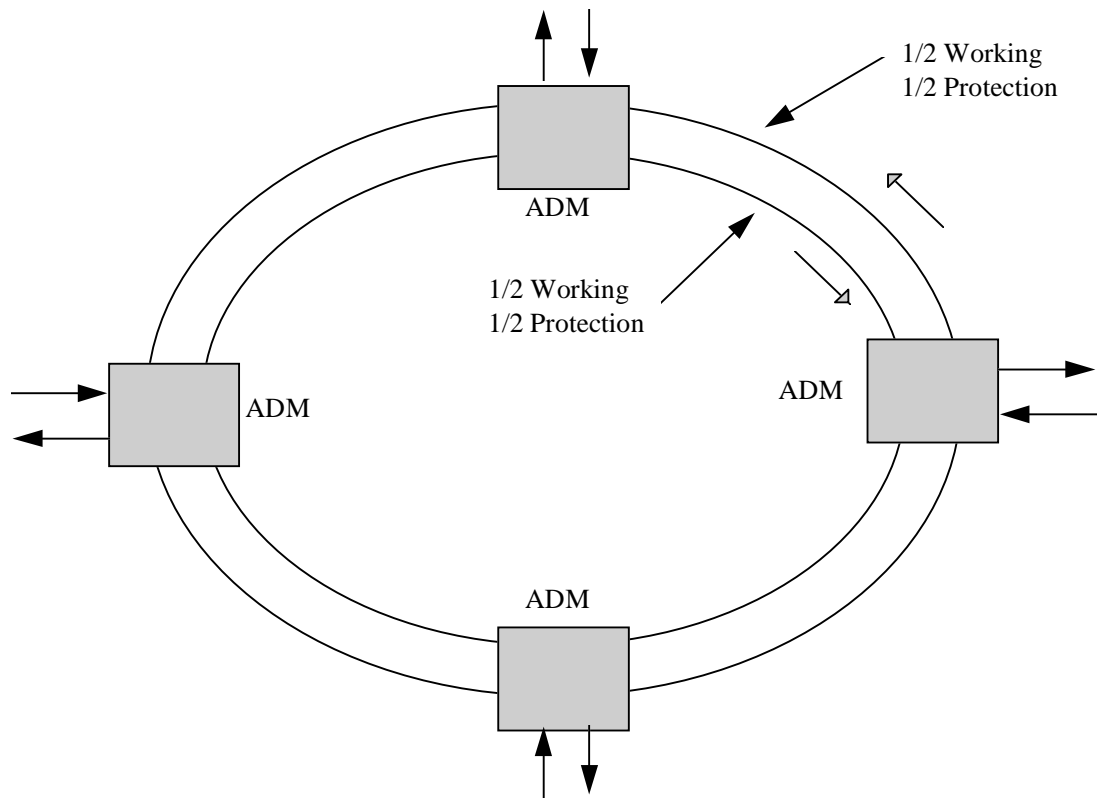
### **“Self Healing” Rings**

There are two primary ring architectures for SONET: bi-directional line-switched rings (BLSRs) and unidirectional path-switched rings (UPSRs).

#### **Bidirectional line switched rings**

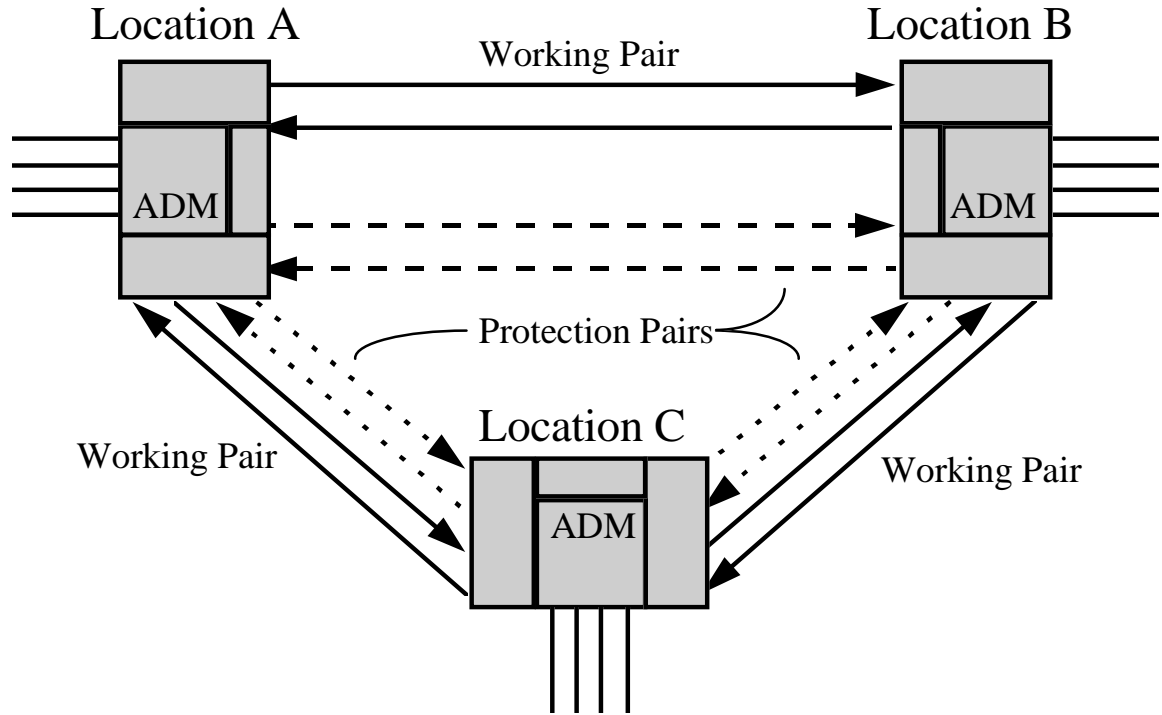
BLSRs are highly survivable and can be implemented using either two or four fibers. Although four-fiber BLSRs are more expensive than two-fiber BLSRs, they are also more robust and survivable.

In the two-fiber version, the working and protection channels share capacity on both fibers. Half the capacity of one fiber is assigned to the working channel and traffic is routed in the clockwise direction. The remaining capacity is assigned to the protection channel. Similarly, half the capacity of the second fiber is assigned to traffic heading in the counterclockwise direction, leaving half the capacity unused for the protection channel. Although, this arrangement results in reduced throughput, since half of the capacity in each channel remains unused during normal operation, it allows for the implementation of a type of line switching called “ring switching,” so-called in order to differentiate it from conventional, point-to-point line switching. Should a failure occur between two ADMs, traffic is rerouted in the direction opposite the failure using the protection channels on each fiber.



**Figure 9. Two-fiber Bidirectional Line Switching Ring**

The four-fiber BLSR supports two types of line-switching, providing a high degree of reliability. One of the types supported is ring switching. Ring switching is automatically initiated if both pairs are disrupted or if a ADM failure occurs. The ADMs on each side of the failure will reroute traffic intended for the failed working pair to the protection pair heading in the opposite direction. The new, longer path will then be used to deliver traffic to the destination.



**Figure 10. Four-fiber BLSR**

The second form of line-switching supported by BLSRs is called “span switching.” If the working pair of fibers between two ADMs fails, then the traffic is switched to the protection pair. The traffic in the working pairs between other ADMs remains unswitched, and therefore unaffected. If multiple working pairs fail between various ADMs, then multiple span-switches can exist simultaneously with some sections operating on the protection pair and others operating on the working pair with no negative impact on the network as a whole.

### **Unidirectional path switched rings**

UPSRs are a type of survivable architecture in which working traffic is transmitted in only one direction on only one fiber. Path-level protection is provided by duplicating the traffic and sending it on the protection fiber in the opposite direction. The receiving ADM compares the two copies and uses the best one. In the event of a failure, the receiving ADM detects the loss and automatically uses the duplicate copy.

## **Future Considerations for SONET**

SONET is becoming quite popular as the physical medium to run ATM. Telephone carriers such as NTT, banks such as CitiCorp and other organizations are adopting SONET as a base for their networks. Although SONET seems to be the physical medium of the future, there is still some work that needs to be done to improve its usage. One problem with SONET is its lack of interoperability. There are virtually no SONET circuits that originate on equipment from one vendor and terminate on equipment from another. This may cause problems for network management in the future. Another issue confronting SONET network management is the differences between carrier-based network management. SONET Operations, Administration, Maintenance and Provisioning is based on OSI's Common Management Information Protocol (CMIP) and CMISE while the vast majority of private data networks in the U.S. rely on TL1 (Transaction Logic 1).

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