SONET pocket guide contents

The sun is made of copper

Nowadays, anyone making such a statement would likely be considered quite mad, yet with these words, spoken back in 1861, Johann Philipp Reis began something that has completely changed the world. This nonsense message, just spoken by Reis into his new invention, was clearly heard by the receiving party. The telephone was born. Despite this, the first usable telephone (A.G. Bell, 1876: Patent for electrical and magnetic transmission of sounds) was thought of as little more than a toy.
Today, it would be difficult for us to imagine life without the telephone. Worldwide, there are some 750 million telephone connections in use and the number of Internet users has exploded in the last few years. By the year 2000, according to a forecast from Nortel, there will be almost 475 million Internet users and the number of services provided will also grow rapidly.

Right from the start, network providers have been faced with coping with a steady increase in the number of users and hence in telephone traffic. This has led to the development of various methods and technologies, designed on the one hand to meet the demands of the market and on the other hand to be as economical as possible.

With the advent of semiconductor circuits and the ever-increasing demand for telephone capacity, a new transmission method known as pulse code modulation (PCM) made its appearance in the 1960s. PCM allows multiple use of a single line by means of digital time-domain multiplexing. The analog telephone signal with a bandwidth of 3.1 kHz

is sampled, quantized and encoded and then transmitted at a bit rate of 64 kbit/s. A transmission rate of 1544 kbit/s results when 24 such coded channels are collected together into a frame along with the necessary signaling information. This so-called primary rate (“T1” or “DS1”) is used in the US, Canada and Japan (see Fig. 1).
The growing demand for more bandwidth made more stages of multiplexing necessary. The asynchronous hierarchy is the result. Slight differences in timing mean that justification or stuffing is necessary when forming the multiplexed signals. Inserting or dropping an individual 64 kbit/s channel to or from a higher digital hierarchy requires a considerable amount of complex multiplexer equipment.
Towards the end of the 1980s, a Synchronous Optical Network (SONET) was introduced. This paved the way for a unified network structure on a worldwide scale, resulting in a means of efficient and economical network management for network providers. The networks can easily be adapted to meet the ever-growing demand for “bandwidth-hungry” applications and services.

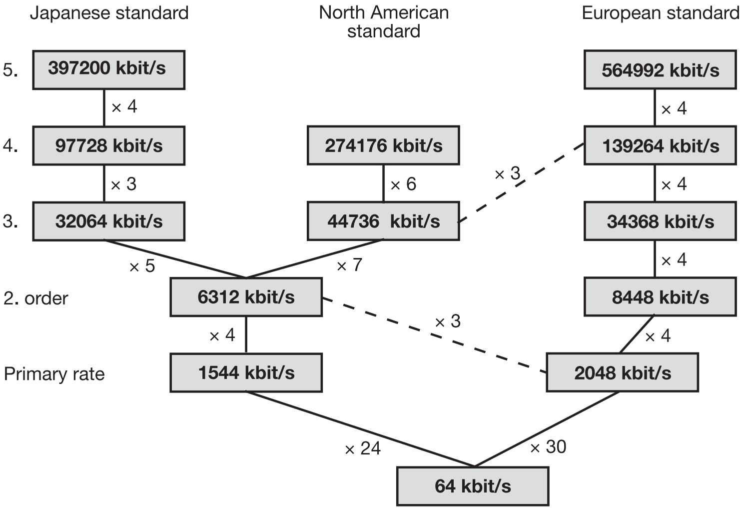


Fig. 1: Summary of plesiochronous transmission rates

Why SONET?

Following the introduction of PCM technology in the 1960s, communications networks were gradually converted to digital technology over the next two decades. To cope with the demand for ever higher bit rates, a complex multiplex hierarchy evolved. The bit rates include the standard multiplex rates of 1.5 Mbit/s and 45 Mbit/s. In many other parts of the world, however, a different multiplex hierarchy evolved based on a primary rate of 2 Mbit/s (often called the “E1”). Because of these very different developments, gateways between one network and another were very difficult and expensive to implement.
The late 1980s saw the initial field trials for SONET (Synchronous Optical NETwork) technology. SONET takes advantage of technological advances in the areas of semiconductors and fiber optics and is superior to asynchronous systems in many ways. The benefits for network providers are as follows:

1. **High transmission rates**
   Transmission rates of up to 10 Gbit/s are standardized in SONET systems. SONET is therefore the most suitable technology for backbones, which can be considered the “superhighways” of today’s telecommunications networks.

2. **Simplified add & drop function**
   Compared with pre-SONET systems, it is much easier to drop and insert low-bit rate channels from or into the high-speed bit streams in SONET. It is no longer necessary to demultiplex and then remultiplex the entire asynchronous mux structure, a complex and costly procedure at best.

3. **High availability and capacity matching**
   With SONET, network providers can react quickly and easily to the requirements of their customers. For example, leased lines can be switched in a matter of minutes. The network provider can use standardized network elements that can be controlled and monitored from a central location by means of a telecommunications management network (TMN).

4. **Reliability**
   Modern SONET networks include various automatic back-up and repair mechanisms to cope with system faults. Failure of a link or a network element does not lead to failure of the entire network, which could be a financial disaster for the network provider.
   These back-up connections are also monitored by a management system.

5. **Future-proof platform for new services**
   Right now, SONET is the ideal platform for services ranging from POTS, ISDN and mobile radio through to data communications (LAN, WAN, etc.), and it is able to handle new, upcoming services such as video on demand and digital video broadcasting via ATM.

6. **Interconnection**
   SONET makes it much easier to set up gateways between different network providers and to SDH systems. SONET interfaces are globally standardized, making it possible to combine network elements from different manufacturers into a network. The result is a reduction in equipment costs compared with pre-SONET.

The driving force behind these developments is the growing demand for more bandwidth, better quality of service and reliability, coupled with the need to keep costs down in the face of increasing competition.
What about the future of transport networks? The trend is towards ever higher bit rates, such as OC-192 (time division multiplex, TDM). The alternative is so-called dense wavelength division multiplexing (DWDM). This is a technology that makes multiple use of single-mode optical fibers possible. Various wavelengths are used as carriers for the digital signals enabling simultaneous transmission over a fiber. Currently available systems permit transmission of 32 wavelengths between 1520 nm and 1580 nm over a single fiber. One OC-48 channel is transmitted at each wavelength, giving a capacity of some 40 Gbit/s per fiber. Expansion to 128 wavelengths has already been announced.
Connected with the introduction of DWDM is the trend towards the "all-optical network". Optical add/drop multiplexers are already available commercially and initial field trials are underway for optical cross-connects. In terms of the ISO-OSI layer model, this development basically enables the introduction of a DWDM layer below the SONET layer (see Fig. 2). The future will therefore likely combine higher multiplex rates with the use of DWDM.

SONET in terms of the layer model

Telecommunications technologies are generally illustrated using so-called layer models. SONET can also be depicted in this way.

SONET networks are subdivided into various layers that are directly related to the network topology. Each layer of the SONET network has it's own overhead information.
The lowest layer is the physical layer, which represents the transmission medium. This is usually a fiber link or occasionally a radio or satellite link.
The section layer is the path between regenerators. Part of the overhead (SOH, section overhead) is available for the signaling required within this layer.
The line layer covers the part of the SONET link between multiplexers. The remainder of the overhead (LOH, line overhead) is used for the needs of the line layer.
The Path Layer covers the link of the SONET network from where the asynchronous digital signals enter and to where these signals exit the SONET network.
The transport modules (synchronous payload envelope, SPE) are designated for carrying the payload. The payload may consist of various signals, each with a particular mapping.
The three VT layers represent a part of the mapping process. Mapping is the procedure whereby the tributary signals (e.g. DSn and ATM signals) are adapted to the SONET transport modules. The DS3 mapping is used for 45 Mbit/s or ATM signals, VT2 mapping for 2 Mbit/s and the VT1.5 mapping for 1.5 Mbit/s signals.

There are other possibilities for SONET transport networks, such as ATM, IP or ISDN which can be mapped into the SPE.

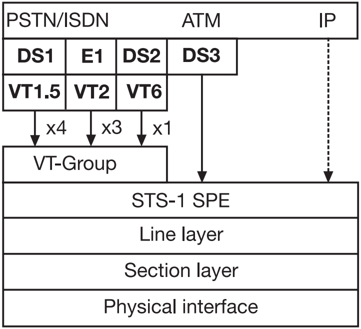


Fig. 2: The SONET layer model

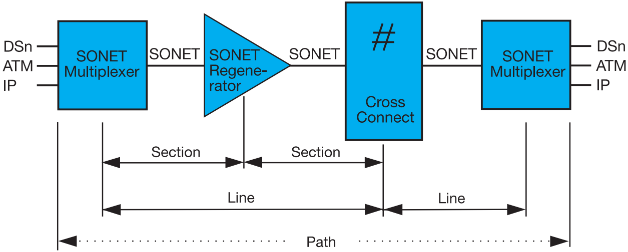


Fig. 3: Path section designations

What are the components of a synchronous network?

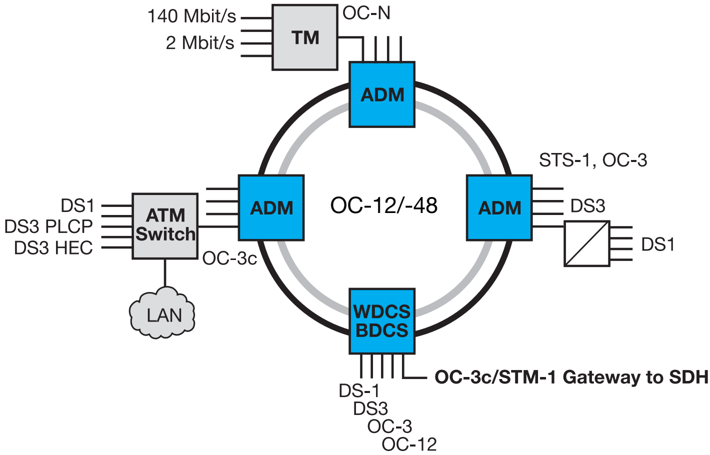


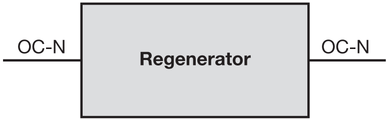
Fig. 4: Schematic diagram of a hybrid communications network

Fig. 6 shows a highly simplified schematic diagram of a SONET ring structure with various tributaries. The mixture of different applications is typical of the data transported by SONET. Synchronous networks must be able to transmit plesiochronous signals and at the same time be capable of handling up and coming services such as ATM. All this requires the use of various network elements. These are discussed in this section.

Current SONET networks are basically made up from four different types of network elements. The topology (i.e. ring or mesh structure) is governed by the requirements of the network provider.

Regenerators

Regenerators, as the name implies, have the job of regenerating the clock and amplitude relationships of the incoming data signals that have been attenuated and distorted by dispersion. They derive their clock signals from the incoming data stream. Messages are received by dropping various 64 kbit/s channels (e.g. service channels E1, F1) from the SOH (section overhead). Messages can also be output using these channels.

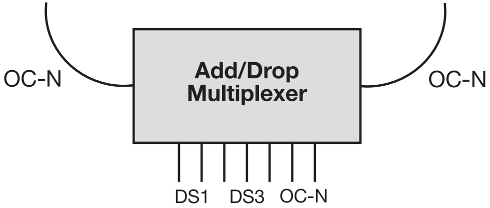


Terminal multiplexers

Terminal multiplexers are used to combine DSn and synchronous input signals into higher bit rate OC-N signals.

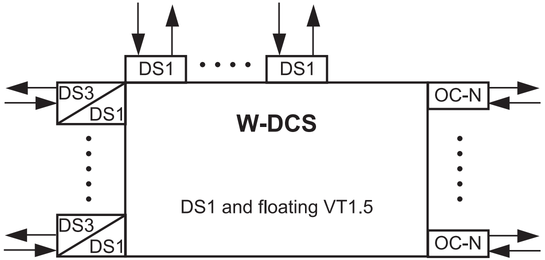
Add/Drop Multiplexers (ADM)

Plesiochronous and lower bit rate synchronous signals can be dropped from or inserted into SONET bit streams by means of ADMs. The remaining traffic is not affected. This feature makes it possible to set up ring structures, which have the advantage that automatic back-up path switching is possible using protection bandwith in the ring in the event of a fault.



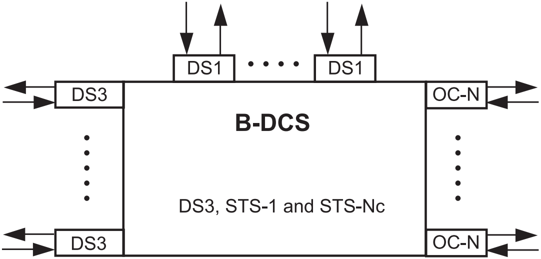
Wideband digital cross connects (W-DCS)

This network element has the widest range of functions. A cross connect can drop containers from any OC-N signal. The received signals can be connected from any input port to any output port at the different levels, even with asynchronous signals.
A W-DCS accepts OC-N signals as well as STS-1, DS-1 and DS-3 signals. Switching is at DS-1 and VT1.5.



Broadband digital cross connects (B-DCS)

Compared to the W-DCS, a broadband DCS can switch signals at the DS-3, STS-1 and STS-Nc levels. A B-DCS has OC-N, STS-1, DS-3, DS-1 and ATM interfaces.



The telecommunications management network (TMN) is a further element of synchronous networks. All the SONET network elements so far mentioned are software-controlled. This means that they can be monitored and remotely controlled, one of the most important features of SONET. Network management is described in more detail in the section “TMN in the SONET network”.

Fiber is the physical medium of choice in SONET. The advantage of optical fibers is that they are not susceptible to interference and they can transmit at very high speeds (also see under DWDM). Single-mode fibers for the first and second optical windows (1 310 nm and 1 550 nm) are preferred.

The STS-1 frame format

The base transmission rate in SONET is 51.84 Mbit/s. This frame is called the synchronous transport signal (STS). Since the frame is the first level of the synchronous digital hierarchy, it is known as STS-1. Fig. 5 shows the format of this frame. It is made up from a byte matrix of 9 rows and 90 columns. The first three columns are reserved for the transport overhead (TOH), while the remaining 87 rows are for transporting the synchronous payload envelope (SPE). Transmission is row by row, starting with the byte in the upper left corner and ending with the byte in the lower right corner. The frame repetition rate is 125 µs.

The payload capacity enables transport of one DS-3 signal, 28 × DS-1 signals or 21 × 2 Mbit/s signals. When this bit rate is transmitted via a fiber system, it is known as OC-1 (Optical Carrier).

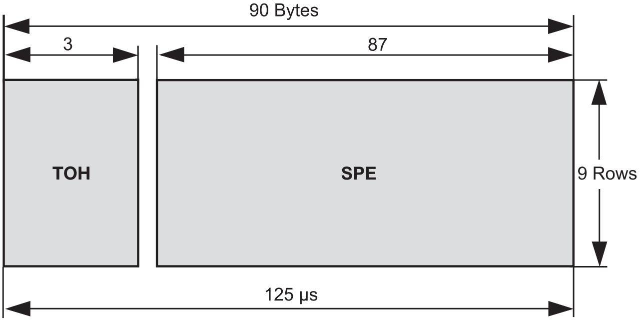


Fig. 5: Schematic diagram of the STS-1 frame

Transport Overhead (TOH)

The STS-1 transport overhead consists of a section overhead and line overhead. The reason for this is to be able to couple the functions of certain overhead bytes to the network architecture. The table below describes the individual functions of the bytes.

Section OH	A1	A2	C1	
	B1	E1	F1	
	D1	D2	D3	
Line OH	H1	H2	H3	Pointer
	B2	K1	K2	
	D4	D5	D6	
	D7	D8	D9	
	D10	D11	D12	
	S1	M0	E2	

Fig 6: Summary of the STS-1 overhead

Overhead byte	Function	Description
A1, A2	Frame synchronization	These bytes indicate the beginning of an STS-1 frame.
B1, B2	Section and line parity bytes	The parity of each particular frame section is formed within a group of 2, 8 or 24 bits. These bit groups are arranged in columns and the parity of each individual bit in the vertical direction is calculated.
D1 to D3	Section DCC	The Data Communication Channels (DCC) allow the transmission of managment and status information.
D4 to D12	Line DCC	
E1, E2	Section and line orderwire bytes	These bytes are allocated as order-wire channels for voice communication.
F1	Section user's data channel	Allocated for user's purposes.
J0 (C1)	Section trace	Contains a plain text sequence.

K1, K2	Automatic protection switching (APS) control	Used to control APS in the event of extreme communications faults.
S1	Synchronization status byte	The S1 byte indicates the signal clock quality and clock source.
M0, M1	Remote error indication	Contains the number of detected anomalies. (M0 only for STS-1/ OC-1)

Table 1: Overhead bytes and their functions

STS path overhead

The STS path overhead (STS POH) is part of the synchronous payload envelope (SPE). The STS POH has the task of monitoring quality and indicating the contents of STS SPE.

J1	Path trace byte
B3	Path parity byte
C2	Path signal label byte
G1	Remote error and defect indication
F2	Path user data channel
H4	Multiframe indication
Z3	Growth
Z4	Growth
Z5	Tandem connection monitoring

Fig. 7: Structure of the STS-1 path overhead

VT path overhead

The VT path overhead is part of the VT (Virtual Tributary is explained in the chapter "How are DSn and ATM signals transported by SONET?"). This overhead enables communications between the generation point of a VT and the destination where the VT is disassembled.

V5	Indication and error monitoring
J2	Signal label
Z6	Tandem connection monitoring
Z7	Growth/RDI-V

Fig. 8: Structure of the VT path overhead

The V5 byte contains the same functions formed in the STS path by the B3, C2 and G1 bytes (see Fig. 9).

Fig. 9: Structure of the V5 byte

BIP-2		REI-V	RFI-V	Signal label			RDI-V
1	2	3	4	5	6	7	8

Bits 1 and 2: Performance monitoring

Bit 3: REI-V (remote error indication) for VT path

Bit 4: RFI-V (remote failure indication) for VT path

Bits 5 to 7: Allocated for a VT path signal label

Bit 8: RDI-V (remote defect indication) for VT path

How are DSn and ATM signals transported by SONET?

The nature of modern networks makes it necessary to be able to transport all asynchronous and ATM signals via the SONET network. The process of matching the signals to the network is called mapping. The virtual tributary SPE is the basic package unit for tributary channels with bit rates below 45 Mbit/s (DS3).

A special virtual tributary SPE (VT-n SPE) is provided for each tributary signal. These VT-n SPEs are always somewhat larger than the payload to be transported. The remaining capacity is used partly for justification (stuffing) in order to equalize out timing inaccuracies in the asynchronous signals.

Together, the VT-n SPE and VT-n POH form the VT-n. This is transmitted unchanged over a path through the network. The next step is the combination of several VTs into VT groups. VTs of different types may not be mixed within a single group. Each VT group consists of a specific VT type. The VT group has a defined size of 9×12 bytes. The number of combined VTs is thus dependent on the VT type (see example in Fig. 11: $4 \times$ VT1.5 = VT group).

Different asynchronous tributary signals can be mapped into an STS-1 frame in this manner. Seven VT groups fill the STS-1 SPE.

Together with the transport overhead, the STS-1 SPE forms an STS-1.

DS3 and E3 (34 Mbit/s) signals are directly mapped into the STS-1 SPE.

Mapping of a 140 Mbit/s (E4) signal is a special case. The transport capacity of an STS-1 is no longer sufficient. This is why this signal must be directly packed into an STS-3 SPE.

This STS-3c mapping is typically tused for ATM signals.

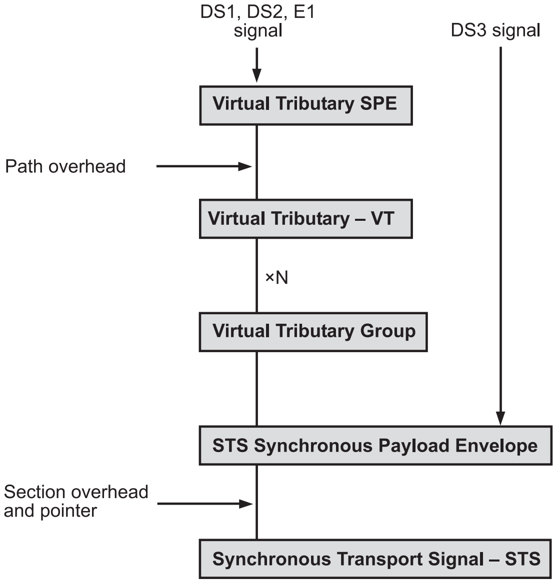


Fig. 10: Insertion of tributary signals into an STS frame

ATM signals can be transported directly using STS-1 SPE or as a payload of an DS1 or DS3 signal. Since a single STS-1 does not meet the fast growing demand for ATM bandwidth, SONET permits transmitting the ATM payload in a multiple STS-N SPE (contiguous concatenation; see the section on “Contiguous concatenation”).
Fig. 11 gives an overview of current mappings.

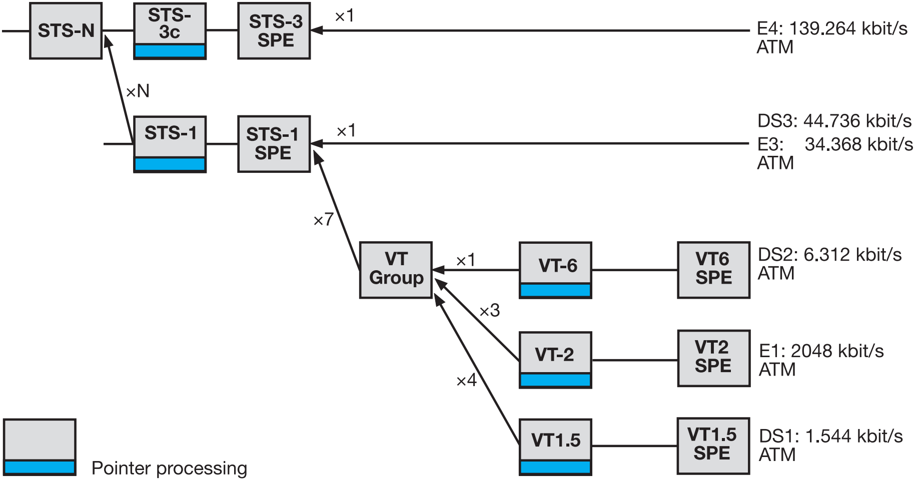


Fig. 11: SONET multiplexing

What is the difference between SDH and SONET?

SDH stands for synchronous digital hierarchy. SDH is the synchronous technology used everywhere except the US, Canada and Japan. Development of this international counterpart to SONET began a few years after SONET. The differences between SONET and SDH are based primarily on the different asynchronous bit rates that must be mapped into them. In developing these two technologies, there was a need to integrate existing transmission techniques in order to enable network operators to gradually introduce SONET and SDH.
Because the highest-order commonly used multiplex signal in N.A. is 45 Mbit/s, 51 Mbit/s was a sufficient synchronous primary rate for virtually any SONET application. However in the rest of the world, where 140 Mbit/s mux signals are very common, 155 Mbit/s (STM-1) was chosen as the primary synchronous mux rate. This bit rate is exactly the same as the STS-3 or OC-3 bit rate.

SONET signals		**Bit rates**	**Equivalent SDH signal**
STS-1	OC-1	51.84 Mbit/s	STM-0
STS-3	OC-3	155.52 Mbit/s	STM-1
STS-12	OC-12	622.08 Mbit/s	STM-4
STS-48	OC-48	2 488.32 Mbit/s	STM-16
STS-192	OC-192	9 953.28 Mbit/s	STM-64

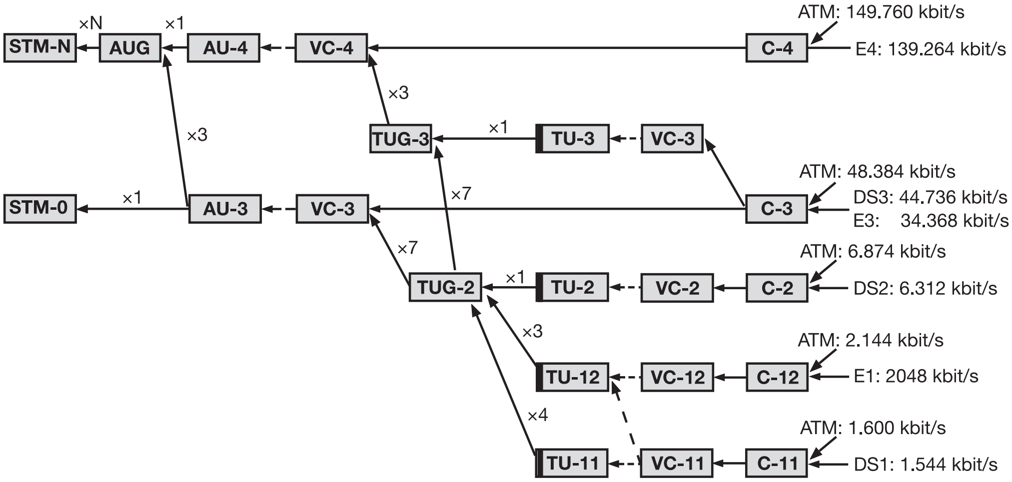


Fig. 12: SDH mapping

As can be gathered from the table, SONET and SDH overlap. Adaptation is relatively simple since gateway problems were taken into account in specifying SDH and SONET. Just a few overhead bytes need to be adapted.

Pointer procedures

The use of pointers gives synchronous communications a distinct advantage over the pre-SONET asynchronous hierarchy. Pointers are used to localize individual synchronous payload envelopes (SPE) in the payload of the synchronous transport signal (STS). The pointer may directly indicate individual SPEs (e.g. DS3 mapping) from the line overhead of the STS-1 frame. Chained pointer structures can also be used (floating VT mode).

Note that there are different ways of mapping a payload into a VT. In "locked mode", no pointer is required since a fixed byte-oriented mapping is used with limited flexibility. The locked mode is considered obsolete and is no longer supported in the SONET standards.

"Floating mode mappings" use a pointer to enable displacement of the payload in the payload area of the VT. This is the usual mapping mode (see also Fig. 13).

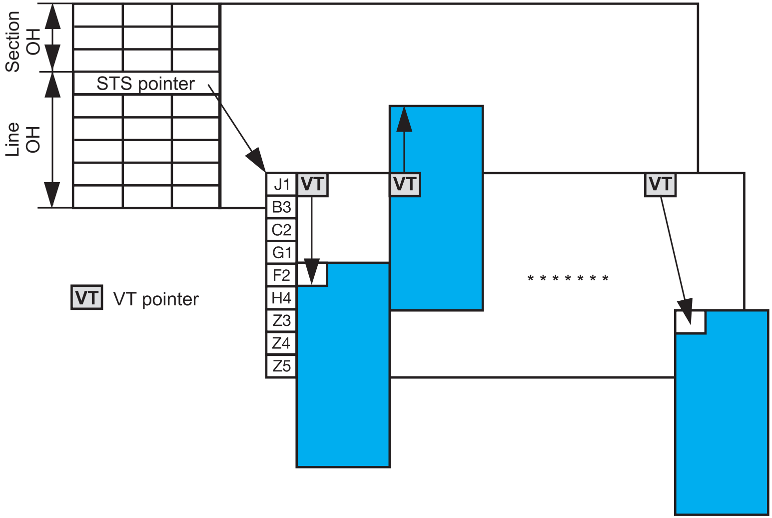


Fig. 13: Floating VT mode

SONET multiplexers are controlled with a highly accurate central clock source running at 1.5 Mbit/s. Pointer adjustment may be necessary if phase variations occur in the real network or if the connection is routed via networks operated by different carriers.
The STS pointer can be altered in every fourth frame with prior indication. The SPE is then shifted by exactly 1 byte. If an additional byte must be inserted, we speak of positive stuffing. Negative stuffing is a shifting of the payload into the H3 byte of the overhead (see Fig. 14). Pointer activity is an indication of clock variations within a network.

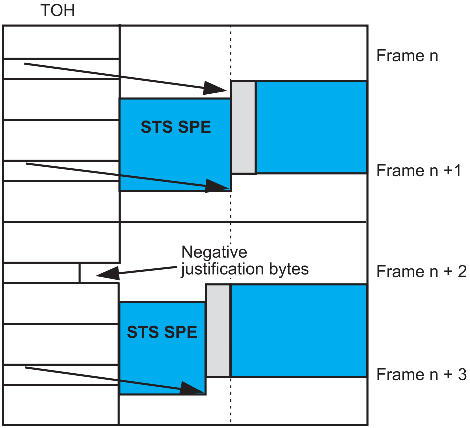


Fig. 14: Negative stuffing

The use of pointers enables, on the one hand, flexible insertion in time of user signals into the next higher frame structure in the form of synchronous payload envelopes (SPEs) without the need for larger buffers. On the other hand, changes in the phase location of the SPE relative to the superior frame can be corrected by appropriate pointer actions. Such changes and shifts in phase can be caused by changes in propagation delay in the transmission medium or by non-synchronous branches in the real network. PJEs (Pointer Justification Events) can be caused by ATM or LAN/WAN equipment with inferior clocks, or by mistakes in provisioning SONET NEs.
When a path is terminated, pointer procedures make it possible to immediately locate every user channel from each STS-N or OC-N frame, which considerably simplifies drop & insert operations within a network node. In contrast, complete demultiplexing of every level of an asynchronous digital hierarchy signal is required in order to access a particular tributary channel.

OC-12c contiguous concatenation

This transmission method is designed to allow bit rates in excess of the capacity of the STS-3c SPE (>150 Mbit/s) to be transmitted. For example, OC-12c is intended for transporting ATM cells. The advantage of this method is that an ATM cell stream with a 600 Mbit/s bandwidth can be transported with a uniform SPE within an OC-12. Four STS-3c SPEs are concatenated to form a 600 Mbit/s payload capacity by setting all pointers except the first to a fixed value known as the concatenation indicator (CI). If pointer activity becomes necessary, this takes place equally for all concatenated STS-3cs. Fig. 15 shows how the payload of ATM cells can be transmitted as a whole.

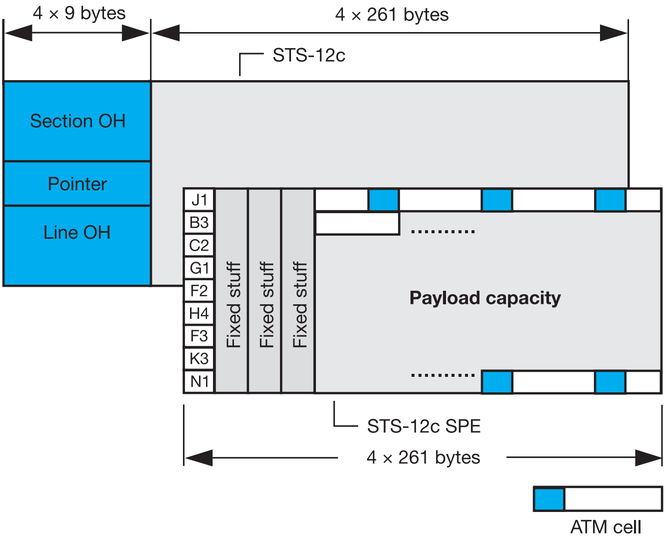


Fig. 15: Contiguous concatenation

Transmission at higher hierarchy levels

SONET provides a wide range of bit rates. Byte-interleaved multiplexing is the basis for this. The following hierarchy levels are defined:

STS-1/OC-1	51.84 Mbit/s
STS-3/OC-3	155.52 Mbit/s
STS-12/OC-12	622.08 Mbit/s
STS-48/OC-48	2488.32 Mbit/s
STS-192/OC-192	9953.28 Mbit/s

An STS-N signal comprises N byte-interleaved STS-1 signals.

Maintenance signals

Numerous alarm and error messages are built into SONET. They are known as defects and anomalies, respectively. They are coupled to network sections and the corresponding overhead information. The advantage of this detailed information is illustrated as follows:
Complete failure of a connection results, for example, in a LOS alarm (loss of signal) in the receiving network element. This alarm triggers a complete chain of subsequent messages in the form of AIS (alarm indication signals; see Fig. 16). The transmitting side is informed of the failure by the return of an RDI alarm (remote defect indication). The alarm messages are transmitted in defined bytes in the TOH or POH. For example, byte G1 is used for the RDI-P alarm.

SONET alarm scheme

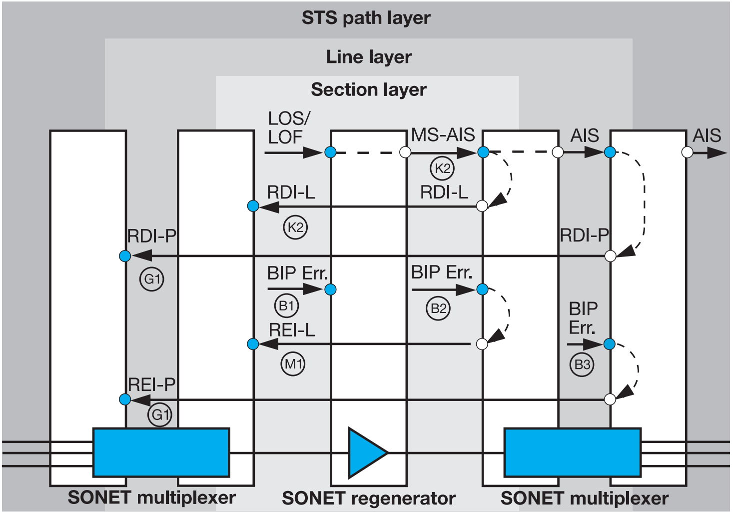


Fig. 16: Overview of major defects and anomalies

If the received signal contains bit errors, the receiving network element detects and reports BIP errors. Since this is not the same as a complete failure of the connection, the alarm here is referred to as an anomaly that is indicated back in the direction of transmission.

The return message is called a REI (remote error indication). Table 2 is a list of all possible defects and anomalies, their meanings and the detection criteria.

	Anomalies/Defects	**Detection criteria**
LOS	Loss of Signal	All-zero pattern for 2.3 µs ≤ T ≤ 100 µs
SEF	Severely Errored Framing	A1, A2 errored for ≥ 625 µs
LOF	Loss of Frame	If SEF persists for ≥ 3 ms
S-BIP Error	Section BIP Error (B1)	Mismatch of the recovered and computed BIP-8 Covers the whole STS-N frame
L-BIP Error	Line BIP Error (B2)	Mismatch of the recovered and computed N × BIP-8 Covers the whole frame, except Section Overhead
AIS-L	Line AIS	K2 (bits 6, 7, 8) = 111 for ≥ 5 frames
REI-L	Line Remote Error Indication	Number of detected B2 errors in the sink side encoded in byte M0 or M1 of the source side

RDI-L	Line Remote Defect Indication	K2 (bits 6, 7, 8) = 110 for ≥ z frames (z = 5 to 10)
AIS-P	STS Path AIS	All "1" in the STS pointer bytes H1, H2 for ≥ 3 frames
LOP-P	STS Path Loss of Pointer	8 to 10 NDF enable 8 to 10 Invalid pointers
P-BIP Error	STS Path BIP Error (B3)	Mismatch of the recovered and computed BIP-8 Covers entire STS-SPE
UNEQ-P	STS Path Unequipped	C2 = "0" for ≥ 5 (≥3 as per T1.231) frames
TIM-P	STS Path Trace Identifier Mismatch	Mismatch of the accepted and expected Trace Identifier in byte J1 (64 bytes sequence)
REI-P	STS Path Remote Error Indication	Number of detected B3 errors in the sink side encoded in byte G1 (bits 1, 2, 3, 4) of the source side
RDI-P	STS Path Remote Defect Indication	G1 (bit 5) = 1 for ≥ 10 frames

PLM-P	STS Path Payload Label Mismatch	Mismatch of the accepted and expected Payload Label in byte C2 for ≥ 5 (≥ 3 as per T1.231) frames
LOM	Loss of Multiframe	Loss of synchronization on H4 (bits 7, 8) superframe sequence
AIS-V	VT Path AIS	All “1” in the VT pointer bytes V1, V2 for ≥ 3 superframes
LOP-V	VT Loss of Pointer	8 to 10 NDF enable 8 to 10 invalid pointers
V-BIP Error	VT Path BIP Error (BIP-2)	Mismatch of the recovered and computed BIP-2 (V5 bits 1, 2) Covers entire VT
UNEQ-P	VT Path Unequipped	V5 (bits 5, 6, 7) = 000 for ≥ 5 (≥ 3 as per T1.231) superframes
TIM-V	VT Path Trace Identifier Mismatch	Mismatch of the accepted and expected Trace Identifier in byte J2
REI-V	VT Path Remote Error Indication	If one or more BIP-2 errors detected in the sink side, byte V5 (bit 3) = 1 on the source side

RDI-V	VT Path Remote Defect Indication	V5 (bit 8) = 1 for ≥ 10 super-frames
PLM-V	VT Path Payload Label Mismatch	Mismatch of the accepted and expected Payload Label in byte V5 (bits 5, 6, 7) for ≥ 5 (≥ 3 as per T1.231) superframes

Table 2: Anomalies and defects in SONET

Back-up network switching

Modern society is virtually a slave to communications technology. Trying to imagine a modern office without any connection to telephone or data networks is like trying to work out how a laundry can operate without water. Network failures, whether due to human error or faulty technology, can be very expensive for users and network providers alike. As a result, the subject of so-called fall-back mechanisms is currently one of the most talked about in the SONET world. Synchronous networks use a wide range of standardized mechanisms to compensate for failures in network elements.

Automatic protection switching (APS)

Two basic types of protection architecture are distinguished in APS. One is the linear protection mechanism used for point-to-point connections. The other basic form is the so-called ring protection mechanism which can take on many different forms. Both mechanisms use spare connections or components to provide the back-up path. Switching is controlled by the overhead bytes K1 and K2.

Linear protection

The simplest form of back-up is known as 1 + 1 APS. Here, each working line is protected by one protection line. The same signal is transmitted on both lines. If a failure or degradation occurs, the network elements switch the connection over to the protection line at the receiving end.

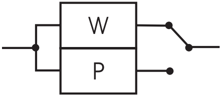


Fig. 17: 1+1 protection scheme

Another approach is the 1:1 configuration. A protection line is used to directly replace the working line when it fails.
The protection path can only be used if a switchover takes place at both the transmitting end and the receiving end. Switching at the far end is initiated by a return message in the backward channel.

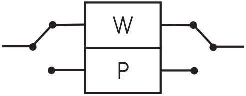


Fig. 18: 1:1 protection scheme

A 1:N configuration represents a more cost-effective solution than the other two mechanisms described above. N working channels are protected by one protection channel. If there are no defects in the network, this protection channel can be used to transport low-priority traffic.

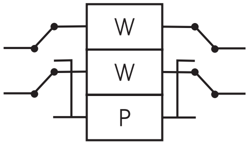


Fig. 19: 1:N protection scheme

The 1 + 1 and 1:1 architectures have 100 % redundancy, as there is a spare line for each working line. Economic considerations have led to the preferential use of 1:N architecture, particularly for long-distance paths. In this case, several working lines are protected by a single back-up line. If switching is necessary, the two ends of the affected path are switched over to the back-up line.
The 1 + 1, 1:1 and 1:N protection mechanisms are standardized in ANSI Recommendation T1.105.1.
The reserve connections can be used for lower-priority traffic, which is simply interrupted if the connection is needed to replace a failed working line.

Ring protection

The greater the communications bandwidth carried by optical fibers, the greater the cost advantages of ring structures as compared with linear structures. A ring is the simplest and most cost-effective way of linking a number of network elements. It offers the highest availability. Various protection mechanisms are commercially available for this type of network architecture, only some of which have been standardized in ANSI Recommendation T1.105.1. A basic distinction is made between ring structures with unidirectional and bi-directional connections.

Unidirectional rings

One method is to use a so-called “path switched ring” (see Fig. 20). Traffic is transmitted simultaneously over both the working line and the protection line. If there is an interruption between network element A and B, the receiver (in this case network element A) switches to the protection line and immediately takes up the connection.
(This is the same as “1+1 protection” already mentioned.)

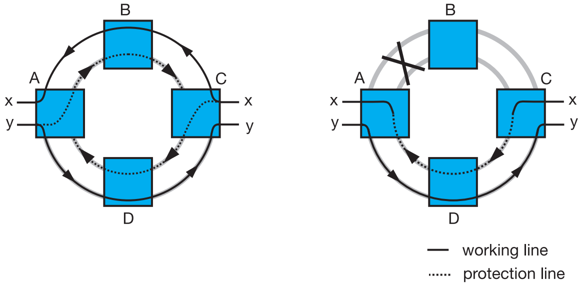


Fig. 20: Two fiber unidirectional path switched ring

Bi-directional rings

In this network structure, connections between network elements are bi-directional. This is indicated in Fig. 21 by the absence of arrows compared to Fig. 20. The overall capacity of the network can be split up for several paths each with one bi-directional working line, while for unidirectional rings, an entire virtual ring is required for each path.
Let us assume that there is an interruption in the connection between network elements A and B. Direction y is unaffected by this fault. An alternative path must, however, be found for direction x. The connection is therefore switched to the alternative path in network elements A and B. The other network elements (C and D) provide a connection for the back-up path. The K1 and K2 bytes in the TOH are used to control the switching process, which is known as a “line switched” process.

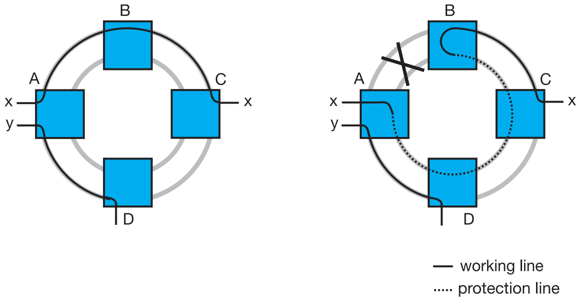


Fig. 21: Two fiber bi-directional line-switched ring (BLSR)

Even greater protection is provided by bi-directional rings with 4 fibers. Each pair of fibers transports working and protection channels. This results in 1:1 protection, i.e. 100 % redundancy. This improved protection is relatively expensive, however.

Synchronization

"Synchronous" is the first word in SONET for a very good reason. If synchronization is not guaranteed, considerable degradation in network function, and even total failure of the network can be the result. To avoid this worst case scenario, all network elements are synchronized to one or more central reference clocks. These reference clocks are generated by highly precise primary reference sources (PRSs) conforming to ANSI Recommendation T1.101 or are received by LORAN or GPS receivers. T1.101 specifies an accuracy of 1×10^{-11} (Stratum 1). This clock signal must be distributed throughout the entire network. A hierarchical structure is used for this; the signal is passed on by the subordinate Stratum 2 (ST2) and Stratum 3 (ST3) clocks.
The synchronization paths can be the same as those used for SONET communications.

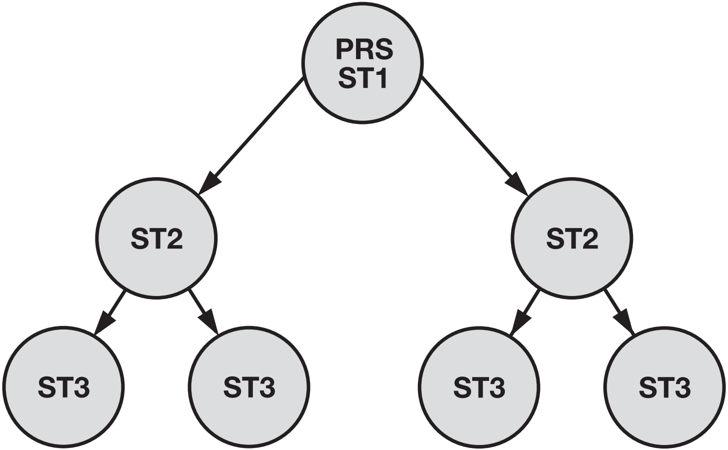


Fig. 22: Clock supply hierarchy structure

The clock signal is regenerated in Stratum 2 and Stratum 3 with the aid of phase-locked loops. If the clock supply fails, the affected network element switches over to a clock source with the same or lower quality, or if this is not possible, it switches to hold-over mode. In this situation, the clock signal is kept relatively accurate by controlling the oscillator with stored frequency correction values for the previous hours and taking the temperature of the oscillator into account. Clock "islands" must be avoided at all costs, as these would drift out of synchronization with the passage of time and a total failure would be the result. Such islands are prevented by signaling the network elements with the aid of synchronization status messages (SSMs, part of the S1 byte). The SSM informs the neighboring network element about the status of the clock supply and is part of the overhead.

Special problems arise at gateways between networks with independent clock supplies. SONET network elements can compensate for clock offsets within certain limits by means of pointer operations. Pointer activity is thus a reliable indicator of problems with the clock supply.

TMN in the SONET network

The basic principles of telecommunications management network (TMN) technology were laid down in ANSI standard T1.210-1993, which is based on Recommendation M.3010 adopted in 1989 by the CCITT (now ITU-T). The functions of a TMN are summed up in the expression "Operation, administration, maintenance and provisioning" (OAM&P). This includes monitoring the network performance and checking error messages, among other things.
To provide these functions, TMN uses object-oriented techniques based on the OSI reference model. The TMN model comprises one manager handling several agents. The agents in turn each handle several managed objects (MO). The manager is included in the operations system (OS) which forms the "network management center" for the network as a whole or in part. In a SONET network, the agents are located in the network elements (NE), such as switches, etc. A MO may be a physical

unit (e.g. a plug-in card, multiplex section, etc.) but can also occur as a logical element (e.g. a virtual connection).
TMN also distinguishes between logical management units. For example, one management unit operates at network level, handling individual NEs. Another management unit operates at the service level, e.g. for monitoring billing charges.
These tasks are performed in modern telecommunications networks by using the common management information protocol (CMIP). It is common to hear about the simple network management protocol (SNMP) in this context, which is basically a simplified version of CMIP. However, SNMP is used mainly in datacom applications and cannot handle the requirements of larger telecom networks. The Q3 interface, which is where the exchange of data between manager and agent takes place, is the point of reference for CMIP. CMIP is also used where several TMNs or their managers are linked together via the X interface.

Since large quantities of data are not generally involved when exchanging information in the TMN, the capacity of the data communication channels (DCC) is sufficient when managing SONET networks. Channels D1 to D3 with a capacity of 192 kbit/s (section DCC) are used for SONET-specific NE management. Channels D4 to D12 with a capacity of 576 kbit/s (line DCC) can be used for non-SONET-specific purposes.

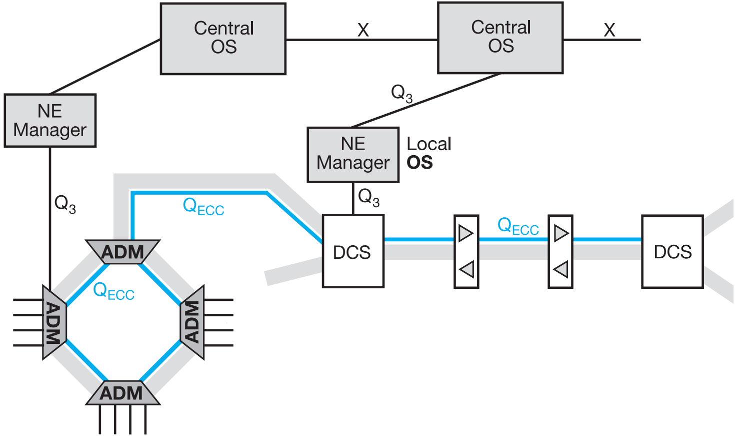


Fig. 23: TMN via OH bytes

To distinguish the implementation in the transport overhead (TOH) data channels from the Q interface, the term QECC protocol is used.

	A1	A2	C1
	B1	E1	F1
Section DCC →	D1	D2	D3
	Pointer		
	B2	K1	K2
	D4	D5	D6
Line DCC →	D7	D8	D9
	D10	D11	D12
	S1	M0	E2

Fig. 24: D bytes in the STS-1 TOH

SONET measurement tasks

Why is separate test technology required for today's TMN-controlled SONET networks? Is it possible to do without any test equipment at all? These or similar questions may arise in your mind, now that you are familiar with the way that SONET networks are constructed and with the basic principles governing their functions. Although trouble-free operation of all network elements should have been guaranteed by standardization on the part of various bodies (ANSI, Bellcore, etc.), problems still arise, particularly when network elements from different sources are linked together. Transmission problems also occur at gateways between networks run by different providers. The test facilities built into the system provide only a rough idea of the location of a fault.

Separate measuring equipment, in contrast, is of much greater usefulness, particularly when it comes to monitoring individual channels. Much more data relevant to correcting the fault can be obtained. The only areas that are covered by both network management and separate test technology are long-term analysis and system monitoring.
Separate test equipment of course has further application in the fields of research & development, production and installation. These areas in particular require test equipment with widely differing specifications.
Take production and installation as an example: Systems manufacturers configure their network elements or entire networks according to customer requirements and use measuring techniques to check that everything operates as it should. Next, the equipment is installed on the customer's site and put into operation. Test equipment is essential at this stage to eliminate any faults that may have occurred during transport and installation, and to verify correct function. Such test equipment needs to be portable and rugged, and capable of performing test sequences in order to reliably and quickly repeat measurements and long-term analyses.
A further example: Network providers. Fault correction and maintenance are the main uses here for measuring equipment. The continuing process of network optimization also plays a major role. Here, too, test equipment must be portable; it must also be reasonably priced and suitable for in-service and out-of-service measurements, and provide users with a rapid and easily interpreted display of the results.
Generally speaking, the following measurement tasks must be handled by SONET test equipment:

- Mapping analysis
- Line-up of port interfaces
- Measurements with structured test signals
- Measurements on add/drop multiplexers
- Delay measurements
- Testing of automatic protection switching (APS)
- Simulation of pointer activity
- In-service SONET measurements
  - Alarm analysis
  - Path trace monitoring
  - Pointer analysis
  - Checking alarm and error sensors built into systems
  - Drop & insert measurements
  - Checking network synchronization
  - Measurements on the TMN interface
- Quality evaluation (e.g. as per ANSI T1.231 and Bellcore GR253)
- Jitter and wander analysis

Some of these measurements are discussed in more detail below.

Anomaly and defect sensor tests

These measurements are performed in order to check the reaction of system components to defects and anomalies. Anomalies are degradation such as parity errors. Defects result in the interruption of a connection.

For example, a network element must react to an LOS (loss of signal) alarm by sending AIS (alarm indication signal) to the downstream network elements and transmitting an RDI (remote defect indication) signal in the return path (see also Fig. 16).

APS response time measurements

A special mechanism is activated in SONET networks in the event of a fault. The faulty link is automatically re-routed over a back-up connection (see "Automatic protection switching (APS)" above). This function is controlled using overhead bytes K1 and K2 ("line switched"). Switching over to the protection line must take place in less than 50 ms. To ensure that this is so, external test equipment is needed.
Test equipment may be used to measure the response time (e.g. loss of a specific test pattern or occurrence of a preset alarm) when a connection is intentionally interrupted (see Fig. 25). The measurement is very important since a delayed response can cause considerable performance degradation or even a total failure of the network (with major loss of income for the network provider).

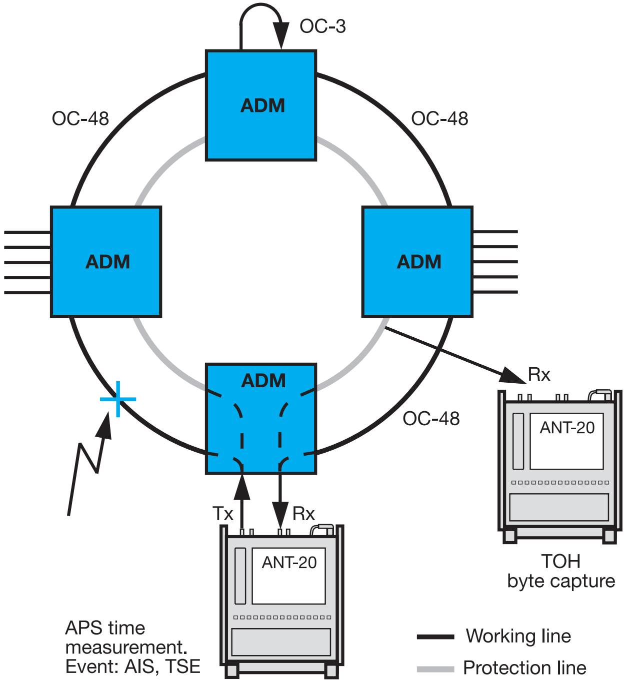


Fig. 25: Checking the APS response time

ANSI/Bellcore performance analysis

When is the performance of a SONET link “good” and when it is “bad”? Transmission path performance is often the subject of a contract between the network provider and the telecommunications user. The results of performance measurements must be broken down into classes for use in the decision-making process. The American standardization bodies ANSI and Bellcore have taken up this issue in their recommendations T1.231 and GR-253 (chapter 6).
Performance measurements are usually made in-service. As part of this measurement, parity bytes B1, B2, B3, BIP-V and the corresponding overhead bytes are evaluated along with the return messages (see Fig. 26).

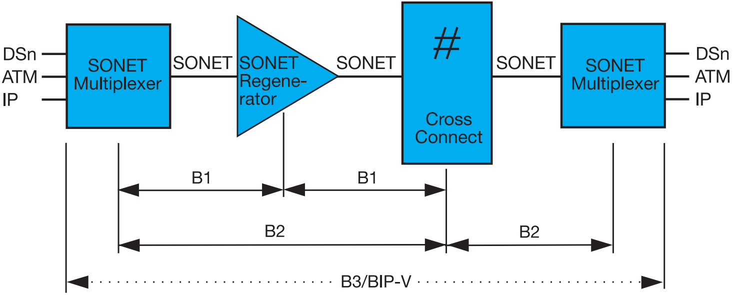


Fig. 26: Allocation of parity bytes to sections

This makes it possible to monitor the performance of the line directly connected to the test set ("near end") as well as the performance of a second connection ("far end") via the return messages.

Table 3: Anomalies and associated OH bytes

Anomaly	**OH byte ("near end")**	**Anomaly, return message**	**Return message OH byte ("far end")**
BIP error	B1	–	–
BIP error	B2	REI-L	M1
BIP error	B3	REI-P	G1
BIP error	BIP-V	REI-V	V5

By evaluating the parity bytes, the following parameters are determined:

- Errored second (ES): A one-second time interval containing one or more bit errors.
- Severely errored second (SES): A one-second time interval in which the bit error ratio is greater than 10^{-3}.
- Unavailable second (US): A connection is considered to be unavailable starting with the first of at least ten consecutive SES. The connection is available from the first of at least ten consecutive seconds which are not SES.
- Severely errored frame second (SEFS): Seconds with OOF (LOF, LOS) in section analysis.

Derived parameter:

- Error-free second (EFS): A one-second time interval in which no bit errors occur.

These parameters refer to the different hierarchy levels (SONET: Section, line, etc.).

Tandem connection monitoring (TCM)

Overhead byte B3 is used to monitor the quality of a path. It is generated at the start and checked at the end of the path. However, it is becoming increasingly necessary to determine the quality of individual segments of a path which might pass through networks operated by different carriers. In such cases, it is especially important to be able to demonstrate that high quality is guaranteed in one's own network. When a fault occurs, the question of who bears the responsibility and the costs of making the repairs is one that needs answering.

Tandem connection monitoring allows monitoring of the performance of path segments with the aid of the N bytes in the POH. The parity bytes of the STS-POH and VT-POH are evaluated by the network elements. The number of errors detected is indicated to the end of the TCM using the N1 or N2 byte. This error count is then compared with the newly determined parity errors. The difference is the number of errors occurring within the TCM.

Jitter measurements

The term jitter refers to phase variations in a digital signal. Put another way, the edges of the digital signal may differ from the expected ideal positions in time. Jitter is described in terms of its amplitude (expressed in unit intervals, UI) and its frequency. If the jitter frequency is below 10 Hz, the term used is wander. Signals that are affected by jitter cannot be sampled accurately; in an extreme situation, this might result in misinterpretation of the input signal. This results in single errors or error bursts and a corresponding degradation in transmission quality. Jitter and wander can also be the cause of buffer underflow or overflow, which leads to bit slips. The theoretical limit for correct sampling at high jitter frequencies is half the bit width. Distortion and additive noise mean that the actual limit must be set much lower than this.
What causes jitter? The clock sources for network elements such as regenerators and add/drop multiplexers are one possible cause. Various types of jitter are differentiated as shown in the following table.

Jitter type	Cause
Mapping jitter	Mapping of asynchronous tributary signals into synchronous transport signals requires bit stuffing in order to match the bit rates. This results in mapping jitter when the signal is demapped.
Pointer jitter	If the SONET transmission bit rates are not synchronous, the timing of the transported STS SPE must be matched to the outgoing frame. This is done by incrementing or decrementing the pointer by one unit.
Intrinsic jitter	Jitter at the output of a device that is fed with a jitter free input signal.
Stuffing and wait time jitter	Non-synchronous digital signals must be matched during multiplexing to the higher bit rate system by the insertion of stuffing bits. These stuffing bits must be removed when the signal is demultiplexed. The gaps which thus occur are equalized out by means of a smoothed clock signal. This smoothing is, however, imperfect, so stuffing and wait time jitter occurs.
Pattern jitter	Distortion in the digital signal leads to so-called inter symbol interference, or time-domain impulse crosstalk. This results in interference between consecutive pulses in a digital signal, which leads to jitter that is pattern-dependent.
Wander	Wander is a slow drift in the significant instants of a digital signal from their ideal equidistant positions in time. These delay variations occur, for example, in optical fibers as a result of daily temperature variations.

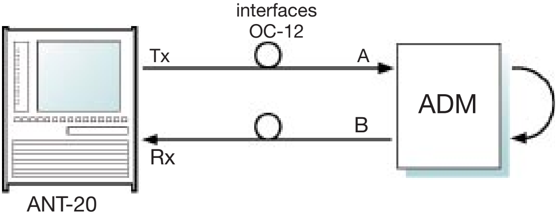
Table 4: Causes of jitter

Other causes of jitter are interference signals and phase noise. Jitter caused by interference signals is also called non-systematic jitter. Phase noise occurs despite the use of a central clock as a result of thermal noise and drift in the oscillator used. Various measurement methods have been developed for the different causes of jitter.

Measurements:

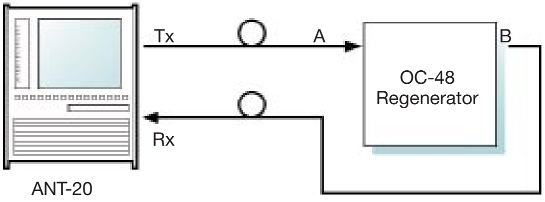
- Maximum tolerable jitter (MTJ)
  Every digital input interface must be able to tolerate a certain amount of jitter before bit errors or synchronization errors occur. The measurement is made by feeding the input of the device under test with a digital signal modulated with sinusoidal jitter from a jitter generator. A bit error tester monitors the output of the device for bit errors and alarms which will occur sooner or later as the jitter amplitude is increased.

Standard	**Requirements for**
ANSI T1.403	DS1
ANSI T1.404	DS3
ANSI T1.105.03	SONET electrical and optical
Bellcore GR253	SONET electrical and optical
Bellcore GR499	DS1 and DS3



- Jitter transfer function (JTF)
  The jitter transfer function (JTF) of a network element indicates the degree to which incoming jitter is passed on to the output.

Standard	**Requirements for**
ANSI T1.403	DS1
ANSI T1.404	DS3
ANSI T1.105.03	SONET electrical and optical
Bellcore GR253	SONET electrical and optical
Bellcore GR499	DS1 and DS3



- Output jitter, intrinsic jitter
  Evaluation of broadband jitter using standardized combinations of high-pass and low-pass filters.

- Mapping jitter
  Due to bit stuffing during the mapping process, gaps arise in the recovered signal during demapping. PLL circuits are used to compensate for these gaps. A certain degree of phase modulation still remains that is known as “mapping jitter”.

Standard	Requirements for
ANSI T1.403	DS1
ANSI T1.404	DS3
ANSI T1.105.03	SONET electrical and optical
Bellcore GR253	SONET electrical and optical

- Pointer jitter **Standards: ANSI T1.105.03 / Bellcore GR253**
  Measurement of allowable pointer jitter is performed by feeding the synchronous demultiplexer with a SONET signal containing defined sequences of pointer activity.

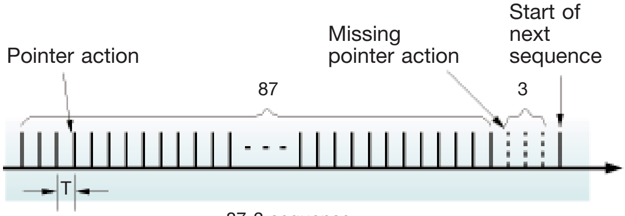
- Combined jitter **Standards: ANSI T1.105.03 / Bellcore GR253**
  Jitter at PDH outputs caused by stuffing during mapping and by pointer activity.

- Wander analysis
  An external, highly precise reference signal is required for performing wander measurements. The phase of the signal under test is compared with the reference signal phase. The very low frequency components require suitably long measurement times (up to 12 days).

Aspects of wander	ANSI/Bellcore standards
Definition and Terminology	T1.101-1994
Network Jitter and Wander, SONET Networks	T1.105.03-1994 T1.102-1993 GR253
Network Jitter and Wander, based on 1.5 Mbit/s	GR499
Primary Reference Source (PRS) Stratum Level 1	T1.101-1994
Stratum Level 2	T1.101-1994
Stratum Level 3	T1.105.09-199x GR1244

Simulating pointer activity

If the jitter behavior of a tributary output in response to pointer activity is to be tested, so-called pointer sequences must be used. Such sequences have been defined by ANSI and BELLCORE in order to guarantee network stability even under extreme conditions.
Once such sequence is known as “87/3 INC”.
This is a sequence of steady pointer increments where 3 pointer actions are omitted after a sequence of 87 actions. This kind of sequence can occur as a result of loss of synchronization in a network element and can cause very large jitter amplitudes.



87-3 sequence

Overview of current ANSI recommendations relevant to SONET

T1.101-1994	Synchronization interface standards for digital networks
T1.102-1993	Digital hierarchy – Electrical interfaces
T1.102.01-1996	Digital hierarchy – VT 1.5 electrical interface
T1.105-1995	SONET – Basic description including multiplex structure, rates and formats
T1.105.01-1995	SONET – Automatic protection
T1.105.02-1995	SONET – Payload mappings
T1.105.03-1994	SONET – Jitter at network interfaces
T1.105.04-1995	SONET – Data communication channel (DCC) protocol and architectures
T1.105.05-1994	SONET – Tandem connection maintenance
T1.105.06-1996	SONET – Physical layer specifications
T1.105.07-1996	SONET – Sub STS-1 interface rates and formats specifications
T1.105.09-1996	SONET – Network element timing and synchronization

T1.119-1994	SONET – Operations, administrations, maintenance and provisioning (OAM&P) communications
T1.119.01-1995	SONET – OAM&P communications, protection
T1.231-1993	Digital hierarchy – Layer 1 in-service digital transmission performance monitoring

Overview of current Bellcore recommendations relevant to SONET

GR253	SONET Transport System: Common Generic Criteria
GR499	Transport System Requirements (TSGR): Common Requirements

SONET abbreviations

A	A1	Section Overhead frame synchronization byte 1111 0110
	A2	Section Overhead frame synchronization byte 0010 1000
	ADM	Add Drop Multiplexer
	AIS	Alarm Indication Signal
	AMI	Alternate Mark Inversion
	ANSI	American National Standards Institute
	APS	Automatic Protection Switching (Channel: K1, K2)
	ATM	Asynchronous Transfer Mode
B	B1	BIP-8 parity word in section layer
	B2	BIP-N $\times$ 24 parity word in line layer
	B3	BIP-8 parity word in STS path layer
	BER	Bit Error Ratio
	BIP-2	BIP-2 parity word
	BIP-N	Bit Interleaved Parity N Bit
	BPS	Bit Per Second
	BSHR	Bi-directional Self Healing Ring
	BLSR	Bi-directional Line Switched Ring
C	C2	Signal label
	CAS	Channel Associated Signaling
	CMIP	Common Management Information Protocol
D	D1-3	196 kbit/s DCC for Section Layer
	D4-12	576 kbit/s DCC for Line Layer
	DCC	Data Communication Channel

	DCN	Data Communication Network
	DCS	Digital Cross Connect
	DSn	Digital Signal
	DWDM	Dense Wavelength Division Multiplexing
E	E1	Electrical Interface Signal 2048 kbit/s
	E2	Electrical Interface Signal 8448 kbit/s
	E3	Electrical Interface Signal 34368 kbit/s
	E4	Electrical Interface Signal 139264 kbit/s
	E1	Section layer orderwire channel
	E2	Line layer orderwire channel
	ECSA	Exchange Carrier Standards Association
F	F1	Section layer user data channel
	F2	Path layer user data channel
	FAS	Frame Alignment Signal
	FEBE	Far End Block Error→See Remote Error Indication (REI)
	FERF	Far End Receive Failure→See Remote Defect Indication (RDI)
G	G1	End-to-end path status
H	H1	Pointer Byte 1: Bit nos. 1 to 4: New Data Flag, Bit no. 5; 6: (Unspecified), Bit no. 7, 8: Pointer value (upper 2 bits)
	H2	Pointer Byte 2: Pointer value (lower 8 bits)
	H3	Pointer Byte 2: Negative Justification Opportunity

	H4	(POH) Payload Indication
I	ISDN	Integrated Services Digital Network
	ISO	International Standardization Organization
J	J0	Section Trace
	J1	Path Trace
	J2	Path Trace
K	K1, K2	APS channels for APS signaling
L	LAN	Local Area Network
	LOF	Loss of Frame
	LOH	Line Overhead
	LOM	Loss of Multiframe
	LOP	Loss of Pointer
	LOS	Loss of Signal
	LTE	Line Terminating Equipment
M	M1	REI byte
	MI	Management Information
	MO	Managed Object
	MTIE	Maximum Time Interval Error
N	N1, 2	Network operator bytes (POH)
	NDF	New Data Flag
	NE	Network Element

O	OAM	Operation, Administration and Maintenance
	OC-N	Optical Carrier, N = 1, 3, 12, 48 and 192
	OH	Overhead
	OOF	Out Of Frame
P	PLL	Phase Locked Loop
	POH	Path Overhead
	PRBS	Pseudo Random Binary Sequence
	PRS	Primary Reference Source
	PTE	Path Terminating Equipment
Q	QoS	Quality of Service
R	RDI	Remote Defect Indication
	REI	Remote Error Indication
	RFI	Remote Failure Indication
	ROSE	Remote Operations Service Element
S	S1	Synchronization status byte
	SDH	Synchronous Digital Hierarchy
	SHR	Self-Healing Ring
	SONET	Synchronous Optical Network
	SPE	Synchronous Payload Envelope
	SPRING	Shared Protection Ring
	ST	Stratum

	STM	Synchronous Transfer Module
	STS	Synchronous Transport Signal
T	TMN	Telecommunications Management Network
	TOH	Transport Overhead
U	UNEQ	Unequipped
	UI	Unit Interval
V	V5	VT-POH byte
	VT	Virtual Tributary
W	WDM	Wavelength Division Multiplexing