SONET

Pocket Guide | **Synchronous Optical Networks**

JDSU

Pocket Guide for Synchronous Optical Networks – Fundamentals and SONET Testing

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Content

Introduction

With some 800 million telephone connections in use today and the number of Internet users continuing to grow rapidly, network providers have been faced with the task of trying to deal effectively with increased telephone and data traffic. In response to the ongoing growing market needs, a number of methods and technologies have been developed within the last 60 years to address these market needs in as economical a way as possible. In the field of communications engineering, this resulted in the introduction of frequency division multiplex (FDM) systems whereby each individual telephone channel was modulated with a different carrier frequency. The signals could then be shifted into different frequency ranges enabling several telephone connections to be transmitted over a single cable.

With the advent of semiconductor circuits and the continuing demand for telephone capacity, a new type of transmission method, pulse code modulation (PCM) was developed in the 1960s.

With PCM (multiple use of a single line by means of digital time domain multiplexing), the analog telephone signal is first sampled at a bandwidth of 3.1 kHz, quantized and encoded then transmitted at a bit rate of 64 kb/s. When 24 such coded channels are collected together into a frame along with the necessary signaling information, a transmission rate of 1544 kb/s is achieved.

This is known as the primary rate and is used throughout USA, Canada, and Japan. The rest of the world uses a primary rate of 2048 kb/s formed by combining 30 channels.

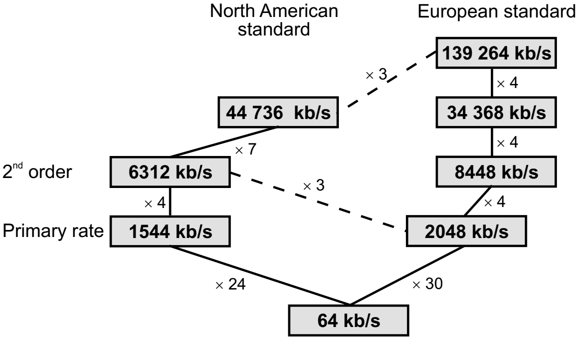
The demand for greater bandwidth however, meant that more stages of multiplexing were needed throughout the world. A practically synchronous – or plesiochronous – digital hierarchy was developed in response. As there are slight differences in timing signals, justification or stuffing is necessary when forming the multiplexed signals.

Inserting or dropping an individual 64-kb/s channel to or from a higher digital hierarchy however requires a considerable amount of complex and expensive multiplexer equipment.

Towards the end of the 1980s, the synchronous optical network (SONET) was introduced, paving the way for a worldwide, unified network structure. SONET is ideal particularly for network providers, as it delivers an efficient, economical network management system that can be easily adapted to accommodate the demand for "bandwidth-hungry" applications and services.

This pocket guide aims to provide an introduction to synchronous communications without going into the "bits and bytes".

Figure 1: Summary of actual plesiochronous transmission rates



Why SONET?

With the introduction of PCM technology in the 1960s, communications networks were gradually converted to digital technology during the years that followed. To cope with the demand for ever-higher bit rates, a multiplex hierarchy or plesiochronous digital hierarchy (DSn) evolved. The bit rates start with the basic multiplex rate of 1.5 Mb/s with a further stage of 45 Mb/s. In many parts of the world however the primary rate is 2 Mb/s with additional stages of 8, 34 and 140 Mb/s. This fundamental difference in developments made the set up of gateways between the networks both difficult and expensive.

In response to the demand for increased bandwidth, reliability, and high-quality service, SONET developed steadily during the 1980s eliminating many of the disadvantages inherent in DSn. In turn, network providers began to benefit from the many technological and economic advantages this new technology introduced including:

High transmission rates

Transmission rates of up to 40 Gb/s can be achieved in modern SONET systems making it the most suitable technology for backbones – the superhighways in today's telecommunications networks.

Simplified add and drop function

Compared to the older DSn system, low bit rate channels can be easily extracted from and inserted into the high-speed bit streams in SONET. It is now no longer necessary to apply the complex and costly procedure of demultiplexing then remultiplexing the plesiochronous structure.

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 (NE) that can be controlled and monitored from a central location via a telecommunications management network (TMN) system.

Reliability

Modern SONET networks include various automatic back-up circuit and repair mechanisms which are designed to cope with system faults and are monitored by management. As a result, failure of a link or an NE does not lead to failure of the entire network.

Future-proof platform for new services

SONET is the ideal platform for a wide range of services including POTS, ISDN, mobile radio, and data communications (LAN, WAN, etc.). It is also able to handle more recent services such as video on demand and digital video broadcasting via ATM.

Interconnection

SONET makes it much easier to set up gateways between different network providers and to SDH systems. The SONET interfaces are globally standardized, making it possible to combine NEs from different manufacturers into a single network thus reducing equipment costs.

The trend in transport networks is toward ever-higher bit rates, such as OC-768 (time division multiplex, TDM). The current high costs of such NEs however are a restricting factor. The alternative lies in dense wavelength division multiplexing (DWDM), a technology enabling the multiple use of single-mode optical fibers. As a result, a number of wavelengths can be used as carriers for the digital signals and transmitted simultaneously through the fibers (See DWDM Pocket Guide for more information).

Connected to the introduction of DWDM is the tendency toward the "all-optical network". Optical cross connects (OXC) are available commercially as well as optical add/drop multiplexers (OADM) and dense wavelength division multiplexing terminals. In terms of the ISO-OSI layer model, this development basically means the introduction of an additional DWDM layer below the SONET layer (see figure 2). Future systems are therefore quite likely to combine higher multiplex rates with the use of DWDM.

The synchronous optical network in terms of a layer model

Telecommunications technologies are generally explained using so called layer models. SONET can also be depicted in the same way.

SONET networks are subdivided into various layers directly related to the network topology. The lowest layer is the physical layer, which represents the transmission medium. This is usually a glass fiber or possibly radio or satellite link. The section layer is the path between regenerators. Part of the section overhead (SOH) is available for the signalling required within this layer.

The remainder of the overhead, the line section overhead (LOH) is used for line section needs. The line section covers the part of the SONET link between multiplexers. 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 Mb/s or ATM signals, VT2 mapping for 2 Mb/s and the VT1.5 mapping for 1.5 Mb/s signals.

The uppermost layer represents the applications of the SONET transport network.

Figure 2: The SONET layer model

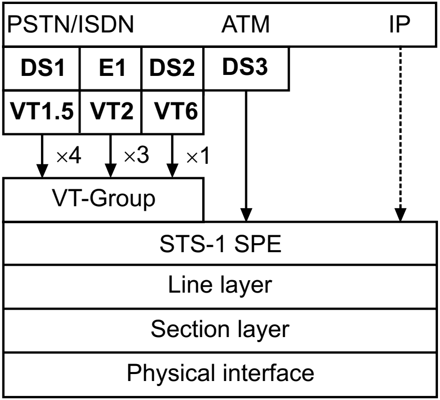
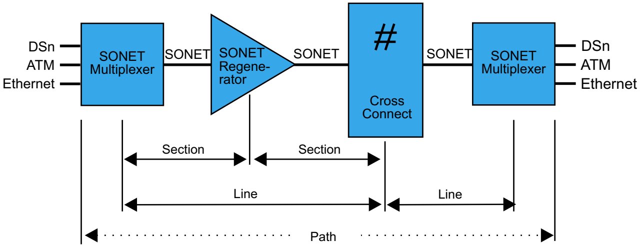


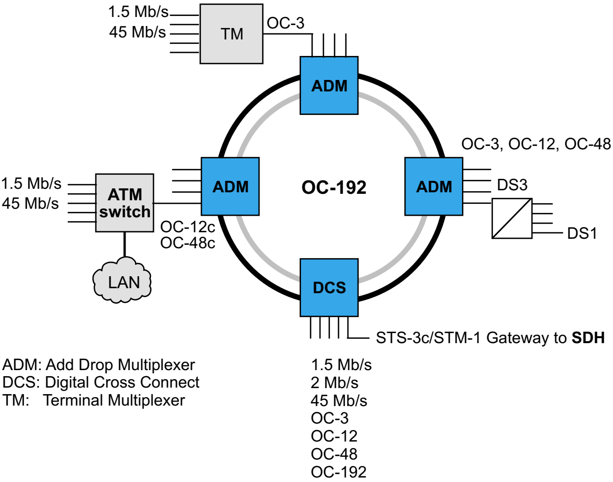
Figure 3: Path section designations



The components of a synchronous network

Figure 4 is a 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 have the ability to transmit plesiochronous signals as well as the capability to handle services such as ATM. This requires the use of the various NEs which are discussed in this section.

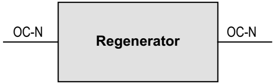
Figure 4: Schematic diagram of hybrid communications networks



Current SONET networks are comprised of five types of NE. The topology (that is the ring or mesh structure) is governed by the requirements of the network provider.

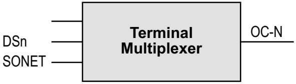
Regenerators

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



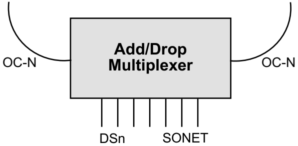
Terminal multiplexers (TM)

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



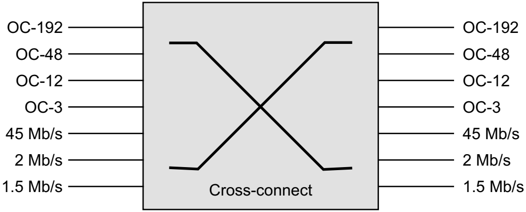
Add/drop multiplexers (ADM)

Plesiochronous and lower bit rate synchronous signals can be extracted from or inserted into high-speed SONET bit streams by means of ADMs. This feature makes it possible to set up ring structures, which have the advantage that in the event of a fault, automatic back-up path switching is possible using elements in the ring.



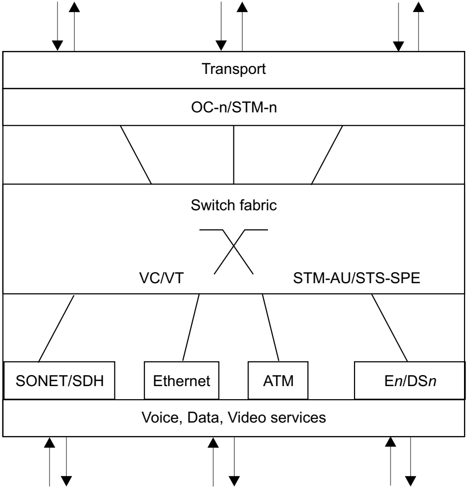
Digital cross-connects (DCS)

This NE has traditionally the function of switching various bitrate input ports to various bitrate output ports.



Multi-Service Provisioning Platform (MSPP)

The increasing demand for quality lead to highly-integrated system components, so called Multi-Service Provisioning Platforms (MSPP) or Multi-Service Switching Platforms (MSSP). These components unite the abilities of ADM, Ethernet switches, routers and DCS with several interfaces, e.g. for different bitrates for Ethernet, SDH and SONET on the transport side and ATM, Ethernet, SDH/SONET, DSn/PDH on the services side.



Network element management

The telecommunications management network (TMN) is also regarded as an element in the synchronous network (more information on TMN in the SONET network can be found on page 55). All the SONET network elements mentioned so far are software-controlled and can thus be monitored and remotely controlled – one of the most important features of SONET.

Optical fibers are the physical medium most commonly used in SONET networks. The advantage of these fibers is that they are not susceptible to interference and can transmit at very high speeds. The disadvantage is in the relatively high cost of procurement and installation. Single-mode fibers are the medium of choice in the first and second optical windows (1310 nm and 1550 nm).

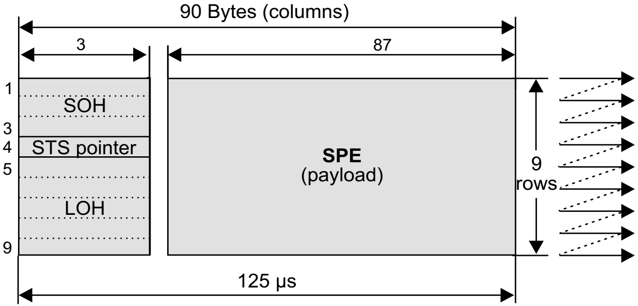
SONET signals can also be transmitted via radio link or satellite paths – a flexible option when setting up transmission paths quickly, as part of a mobile radio network or in difficult terrain. However, the limited bandwidth and complexity in linking such paths into the network management system are a disadvantage.

The STS-1 frame format

The base transmission rate in SONET is 51.84 Mb/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 ms.

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

Figure 5: Schematic diagram of STS-1 frame



Transport overhead (TOH)

The first three bytes in each of the nine rows are called the overhead. There is a distinction between the SOH and the LOH. The reason for this is so that the functions of certain overhead bytes can be coupled with the network architecture. The table below describes the individual functions of the bytes.

Figure 6: Overview of STS-1 overhead

Section OH	A1	A2	J0
	B1	E1	F1
	D1	D2	D3
Pointer	H1	H2	H3
Line OH	B2	K1	K2
	D4	D5	D6
	D7	D8	D9
	D10	D11	D12
	S1	M0	E2

Overhead byte	**Function**
A1, A2	Frame alignment
B1, B2	Quality monitoring, parity bytes
D1 to D3	Q_{ECC} network management
D4 to D12	Q_{ECC} network management
E1, E2	Voice connection
F1	Maintenance
J0	Trace identifier
K1, K2	Automatic protection switching (APS) control
S1	Clock quality indicator
M0	Transmission error acknowledgment

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.

STS POH

J1	Path trace byte
B3	Quality monitoring
C2	Container composition
G1	Communication error return message
F2	Maintenance
H4	Multiframe indication
Z3	Maintenance
Z4	Automatic protection switching
N1	Tandem connection monitoring

VT path overhead

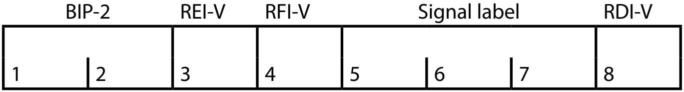
The VT path overhead is part of the VT (Virtual Tributary is explained in the chapter “How are DSn and ATM signals transported by SONET?”). This overhead enables communications between the generation point of a VT and the destination where the VT is disassembled.

VT POH

V5	Indication and error moinitoring
J2	Signal label
Z6	Tandem connection monitoring
Z7	Automatic protection switching

The V5 byte contains the same functions formed in the STS path by the B3, C2 and G1 bytes (see Fig. 7).

Figure 7: V5 byte composition



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, ATM and IP 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 Mb/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. 10: 4 × VT1.5 = VT group).

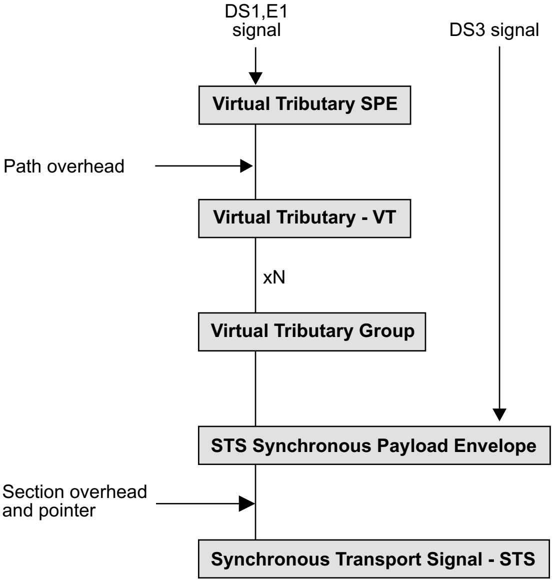
Different asynchronous tributary signals can be mapped into an STS-1 frame in this manner. Seven VT groups fill the STS-1 SPE.

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

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

Mapping of a 140 Mb/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-3c SPE. This STS-3c mapping is typically used for ATM signals.

Figure 8: Insertion of tributary signals into an STS frame



ATM signals can be transported directly using STS-1 SPE or as a payload of a 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").

Data over SONET

The increased Data traffic requires technologies to transport Ethernet or IP packets to the physical layer. This transport below the higher layer is described by Data over SONET, respectively Ethernet over SONET (EoS) and Paket over SONET (PoS). For PoS there is a two-step encapsulation: first the IP packets are encapsulated by a Point-to-Point Protocol (PPP). Second the encapsulation into a High-Data Layer Control-like frame is executed. Ethernet frames are mapped into a frame-mapped GFP and then via virtual concatenation into SONET frames.

Figure 9: Alternative routes to transmit IP packets to the fiber

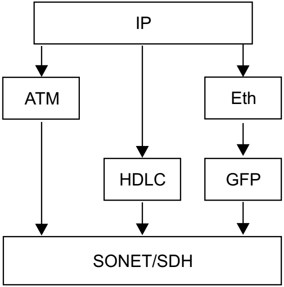
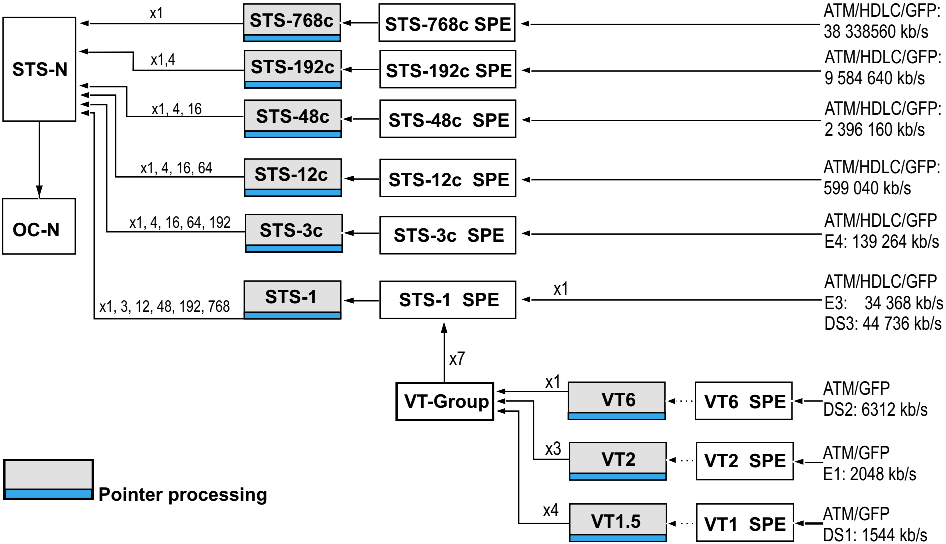


Figure 10 gives an overview of the mappings currently possible according to ATM mapping and ANSI recommendation T1.105.

Figure 10: SONET multiplexing scheme



The differences 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 Mb/s, 51 Mb/s was a sufficient synchronous primary rate for virtually any SONET application. However in the rest of the world, where 140 Mb/s mux signals are very common, 155 Mb/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 signal	Bit rates	Equivalent SDH signal
STS-1 OC-1	51.84 Mb/s	STM-0
STS-3 OC-3	155.52 Mb/s	STM-1
STS-12 OC-12	622.08 Mb/s	STM-4
STS-48 OC-48	2488.32 Mb/s	STM-16
STS-192 OC-192	9953.28 Mb/s	STM-64
STS-768 OC-768	39813.12 Mb/s	STM-256

Table 2: SONET/SDH signal and bit rate hierarchy

These hierarchy levels basically match the plesiochronous bit rates commonly used in these countries.

As the table indicates, there are points where transition between SDH and SONET systems are possible. Matching is relatively simple, as gateway issues were taken into consideration during development of SDH. Only minor adjustments need to be made to certain overhead bytes. SDH terminology is however, quite different with the packing unit for example referred to as a virtual container (VC-n) as opposed to virtual tributary.

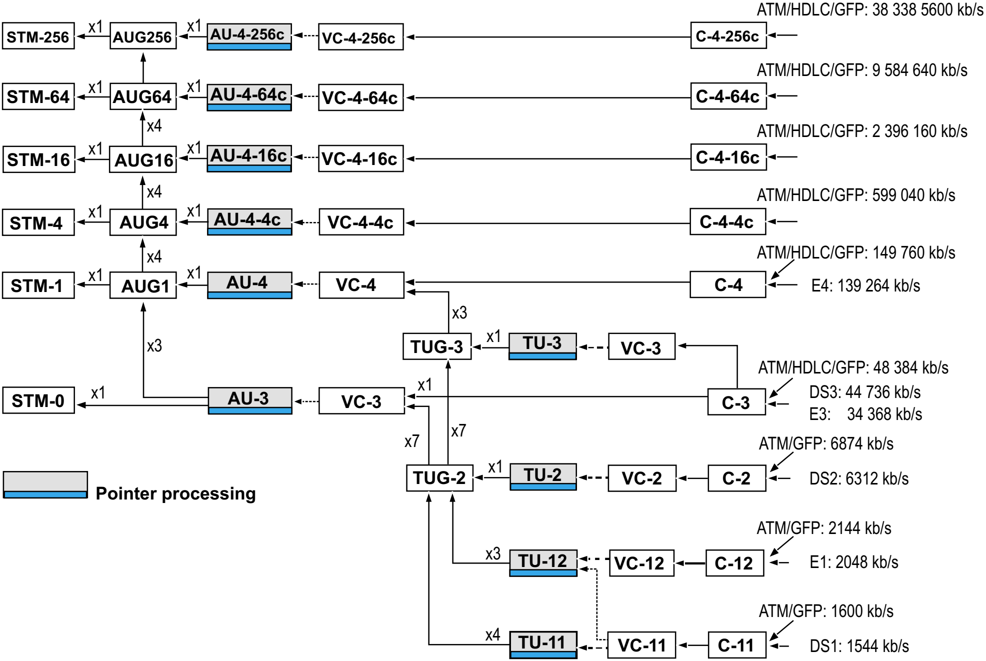


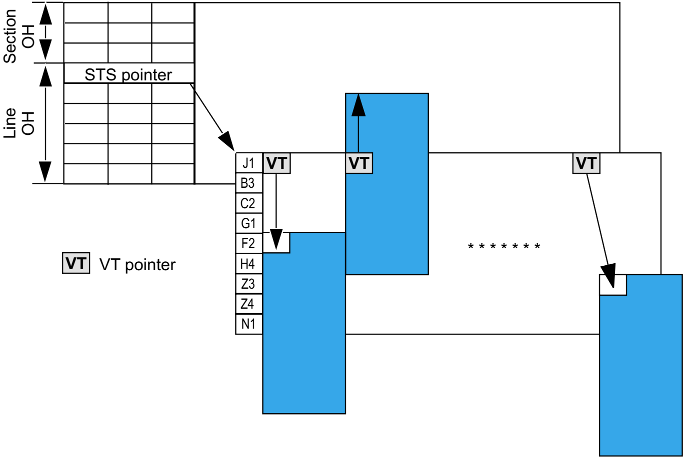
Figure 11: Mapping in SDH

Pointer procedures

The use of pointers gives synchronous communications a distinct advantage over the plesiochronous 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).

Figure 12 illustrates the pointer procedure using floating DS1 mapping as an example.

Figure 12: Schematic diagram of floating DS1 mapping



SONET multiplexers are controlled with a highly accurate central clock source running at 1.5 Mb/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. 13). Pointer activity is an indication of clock variations within a network.

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.

Pointer increment (INC)

If the incoming data signal is slower than the reference clock (“Offset –“), then too little data arrives for the outgoing transport signal.

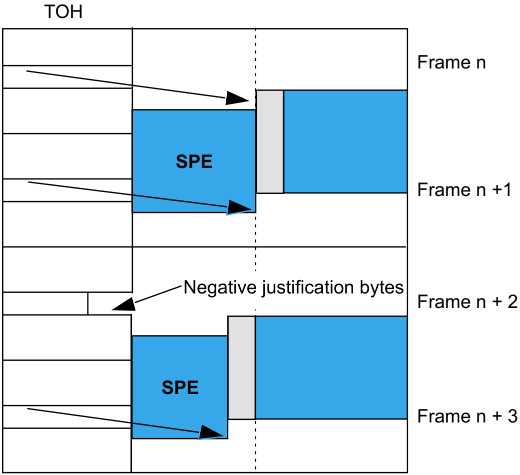
The payload is “shifted forward” virtually and the pointer value increased. The bytes freed up in this process are replaced with stuffing bytes (“positive pointer stuffing”). The effective bit rate for the user data is artificially decreased in this manner.

Pointer decrement (DEC)

If the incoming data signal is faster than the reference clock ("Offset +"), then too much data arrives for the outgoing transport signal. The payload is "shifted backward" virtually and the pointer value decreased. The missing bytes are inserted into the SOH overhead ("negative pointer stuffing").

If the pointer is shifted to a later point in time (to the right in figure 13), the three bytes immediately preceding it are ignored. If the transmitting source is in advance of the actual clock, space for extra capacity must be provided. This takes place at the pointer position into which three bytes are inserted each time. If a further clock adjustment is not made, this configuration is propagated throughout the network.

Figure 13: Negative pointer justification



This allows for the free insertion in time of user signals into the next higher frame structure in the form of virtual containers without the need for larger buffers. However, changes in the phase location of the virtual container 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.

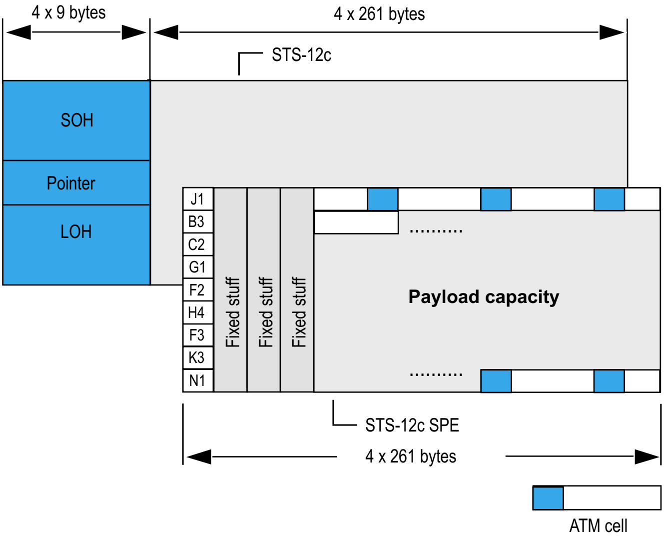
When a multiplex bundle is resolved, pointer procedures make it immediately possible to locate every user channel from each STS-N frame, which considerably simplifies drop and insert operations within a network node. In contrast, complete demultiplexing of every level of a plesiochronous hierarchy signal 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 Mb/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 Mb/s bandwidth can be transported with a uniform SPE within an OC-12. Four STS-3c SPEs are concatenated to form a 600 Mb/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. 14 shows how the payload of ATM cells can be transmitted as a whole.

The first pointer indicates byte J1.All other pointers are set to concatenation indication (CI) ATM Cell.

Figure 14: Contiguous concatenation



Virtual concatenation

To transfer data services (e.g. Ethernet) via SONET the service has to be mapped into the available container sizes.

It’s obvious that the service does not fit exactly into the available container size. Either the containers are too small or the available bandwidth is wasted.

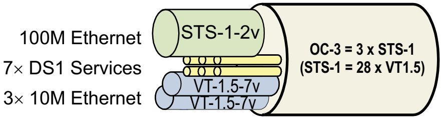
Virtual concatenation (VCat) concatenates several containers VT/STS of the same size to adapt to the required bandwidth.

This is called Virtual Concatenation Group (VCG) which consists of certain “members”.

This allows different services transported in one link

All members of the VCG can be sent out independently, using any path available. At the destination all members are collected and reassembled to the original VCG and the service is demapped.

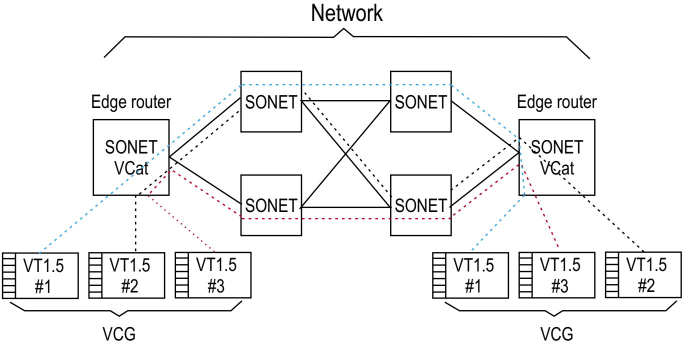
Figure 15: Integrated services by using VCAT



As one advantage the available SONET network can remain the same except the edge elements, which have to support VCAT.

Differential delays between VCG members are likely due to the transportation over different paths with different latencies. Therefore, the destination node must compensate for the different delays before reassembling the payload.

Figure 16: Principle of differential delay

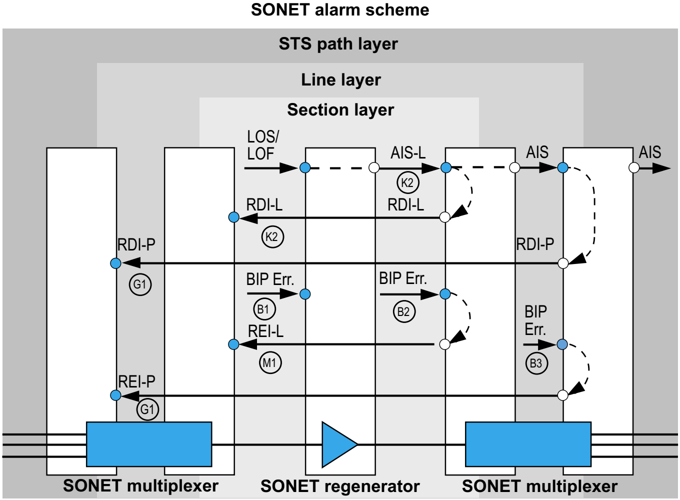


Error and alarm monitoring

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 figure 17). 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.

Figure 17: Overview of major defects and anomalies



If the received signal contains bit errors, the sensor indicates BIP errors. Since this is not the same as a complete failure of the circuit, the alarm here is referred to as an anomaly that is indicated back in the direction of transmission. The return message is referred to as a remote error indication (REI). Table 3 lists the possible defects and anomalies, the corresponding bytes, and their definitions.

Abbreviation	Name	OH byte / Detection criteria
LOS	Loss of Signal	Drop in incoming optical power level causes high bit error rate
TSE	Test Sequence Error (bit error)	
LSS	Loss of Sequence Synchronization	
LTI	Loss of incoming Timing Intervals	
SECTION		
OOF	Out of Frame	A1, A2 errored for 625us
LOF	Loss of Frame	A1,A2 / if OOF persists for 3ms
B1 (8 bits)	Regenerator Section Error Monitoring	B1 / Mismatch of the recovered and computed BIP-8. Covers the whole STS-N frame
TIM-S	Section Trace Identifier Mismatch	J0 / Mismatch of the accepted and expected Trace Identifier
LINE		
AIS-L	Line Alarm Indication Signal	K2 (bits 6, 7, 8) = 111 for > 3 frames
RDI-L	Line Remote Defect Indication	K2 (bits 6, 7, 8) = 111 for > z frames (z = 3 … 5)

Abbreviation	Name	OH byte / Detection criteria
REI-L	Line Remote Error Indication	M1 / Number of detected B2 errors in the sink side encoded in byte M1 of the source side
B2 (24 bits)	Error Monitoring	B2 / Mismatch of the recovered and computed NxBIP-24. Covers the whole frame except SOH
STS – PATH		
LOP-P	Loss of STS Pointer	H1, H2 / 8-10 NDF enable or 8 to 10 invalid pointers
AIS-P	Administrative Unit AIS	STS-1 SPE incl. H1,H2,H3 / All „1" in the STS pointer bytes H1, H2 for ≥ 3 frames
RDI-P	STS path Remote Defect Indication	G1 (bit 5) = "1" for ≥ 10 frames
REI-P	STS path Remote Error Indication	G1 / Number of detected B3 errors at the far-end encoded
TIM-P	STS path Trace Identifier Mismatch	J1 / Mismatch of received and expected TI in byte J1
PLM-P	STS path Payload Label Mismatch	C2 / Mismatch of the received and expected Payload label in byte C2 for ≥ 5 (≥ 3 as per T1.231) frames

Abbreviation	Name	OH byte / Detection criteria
B3 (8 bits)	Error Monitoring	B3 / Mismatch of the recovered and computed BIP-8
UNEQ-P	STS path unequipped	C2 / C2=”0” for ≥ 5 (≥3 as per T1.231) or more frames
VIRTUAL TRIBUTARY PATH (VT)		
LOP-V	Loss of TU Pointer	V1,V2 / 8 to 10 NDF enable, 8 to 10 invalid pointers
AIS-V	TU Alarm Indication Signal	VT incl. V1 to V4 / All “1” in the VT pointer bytes V1, V2 for ≥ 3 superframes
LOM	TU Loss of Multiframe	H4 / Loss of synchronisation on H4 (bits 7, 8) superframe sequence
UNEQ-V	VT Path Unequipped	V5 (bits 5, 6, 7) = 000 for ≥ 5 (≥ 3 as per T1.231) superframes
RDI-V	VT Path Remote Defect Indication	V5 (bit 8) = “1” for ≥ 10 superframes
REI-V	VT Path Remote Error Indication	V5 / If one or more BIP-2 errors detected in the sink side, byte V5 (bit 3) = “1“ on the source side

Abbreviation	Name	OH byte / Detection criteria
TIM-V	VT Path Trace Identifier Mismatch	J2 / Mismatch of received and expected TI in byte J2
PLM-V	VT Path Payload Label Mismatch	V5 / Mismatch of the received and expected Payload Label in byte V5 (bits 5, 6, 7) for ≥ 5 (3 ≥ as per T1.231)
BIP-2	VT Path Error Monitoring	V5 / Mismatch of recovered and computed BIP-2 (V5 bits 1, 2)

Table 3: Errors and Alarms in SONET

Back-up network switching

Modern society is almost completely dependent on communications technology.

Network failures, whether due to human error or faulty technology, can be expensive for users and network providers alike. As a result, the subject of fall-back mechanisms is one of the most discussed in SONET. A wide range of standardized mechanisms has been incorporated into synchronous networks in order 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, which is used for point-to-point connections, and ring protection mechanism, which can take on many different forms. Both mechanisms use spare circuits or components to provide the back-up path. Switching is controlled by the overhead bytes K1 and K2.

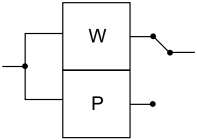
Linear protection

The simplest form of back-up is the so-called 1 + 1 APS, where each working line is protected by one protection line. If a defect occurs, the protection agent in the NEs at both ends switches the circuit over to the protection line. The switchover is triggered by a defect such as LOS. Switching at the far end is initiated by the return of an acknowledgment in the backward channel.

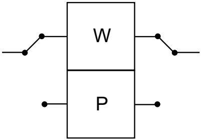
1+1 architecture includes 100 percent redundancy, as there is a spare line for each working line. Economic considerations have led to the preferential use of 1:N architecture, particularly for long-distance paths. Here, several working lines are protected by a single back-up line. If switching is necessary, the two ends of the affected path are switched over to the back-up line.

The 1+1 and 1:N protection mechanisms are standardized in ANSI recommendation T1.105. The reserve circuits can be used for lower-priority traffic, which can simply be interrupted if the circuit is needed to replace a failed working line.

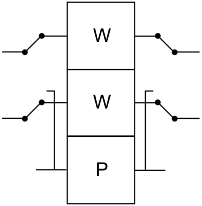
Figure 18: Linear protection schemes



1+1 protection scheme



1:1 protection scheme



1:N protection scheme

Ring protection

The greater the communications bandwidth carried by optical fibers, the higher the cost saving in ring structures when compared with linear structures. A ring is the simplest and most cost-effective way of linking a number of network elements.

A number of protection mechanisms are available for this type of network architecture, some of which have been standardized in ANSI recommendation GR-1400. There are some basic distinctions to be observed however between ring structures with unidirectional and bidirectional connections.

Unidirectional rings

Figure 19 shows the basic principle of APS for unidirectional rings. Assuming an interruption in the circuit occurs between network elements A and B, direction y would be unaffected. An alternative path would however have to be found for direction x. The connection would therefore be switched to the alternative path in NEs A and B while the other NEs (C and D) would switch through the back-up path. This is known as a line-switched process. A simpler method would be to use the path-switched

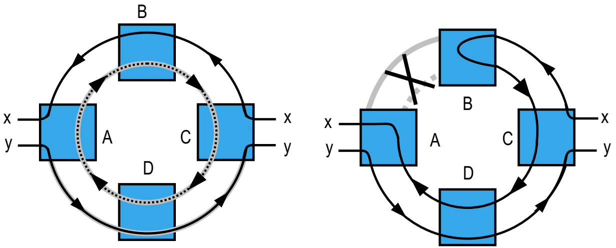


Figure 19: Two-fiber unidirectional line switched ring

ring (figure 20). In this case, traffic would be transmitted simultaneously over both the working and protection line. Should there be an interruption, the receiver (in this case A) would switch to the protection line and immediately take up the connection.

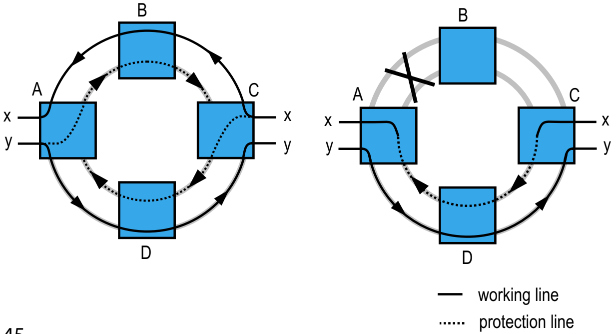


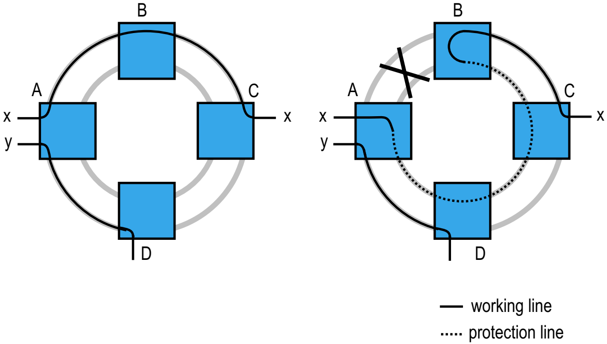
Figure 20: Two-fiber unidirectional path switched ring

Bidirectional rings

In this network structure, connections between NEs are bidirectional (figure 21).The overall capacity of the network can be split up for several paths, each with one bidirectional working line. For unidirectional rings, an entire virtual ring is required for each path. If a fault occurs between neighboring elements A and B, network element B triggers protection switching and controls network element A by means of the K1 and K2 bytes in the LOH.

Bidirectional rings with four fibers provide even greater protection. Each pair of fibers transports working and protection channels. This results in 1:1 protection that is 100 percent redundant. This improved protection is however coupled with relatively high costs.

Figure 21: Two-fiber bidirectional line-switched ring (BLSR) working line protection line



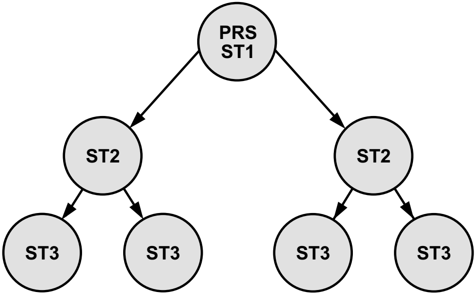
Synchronization

If synchronization is not guaranteed, this can result in considerable degradation in network functionality and even total failure. To avoid such scenarios, all NEs are synchronized to a central clock. This central clock is generated by a high-precision, primary reference source (PRS) unit conforming to ANSI recommendation T1.105. This specifies an accuracy of 1×10^{-11}.

This clock signal must be distributed throughout the entire network. A hierarchical structure is used, in which the signal is passed on by the subordinate Stratum 2 (ST2) and Stratum 3 (ST3) clocks.

The synchronization signal paths can be the same as those used for SONET communications.

Figure 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 NE switches over to a clock source with the same or lower quality. If this is not possible, the NE switches to holdover mode. In this situation, the clock signal is kept relatively accurate by controlling the oscillator, applying the 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 drift out of synchronization over time and lead to total failure. Such islands are prevented by signaling the NEs with the aid of synchronization status messages (SSM – part of the S1 byte). The SSM informs the neighboring NE of the clock supply status and is part of the overhead. Certain problems can arise at the gateways between networks with independent clock supplies.

SONET NEs can compensate for clock offsets within certain limits by means of pointer operations. Pointer activity is thus a reliable indicator of clock supply problems.

Telecommunications management network (TMN) in the SONET network

The principle of telecommunications management network (TMN) technology was established in 1989, with the publication by the CCITT (now ITU-T) recommendation M.3010. The functions of a TMN are expressed as: operation, administration, maintenance, and provisioning (OAM&P). This includes monitoring of network performance and checking of error messages, among other things.

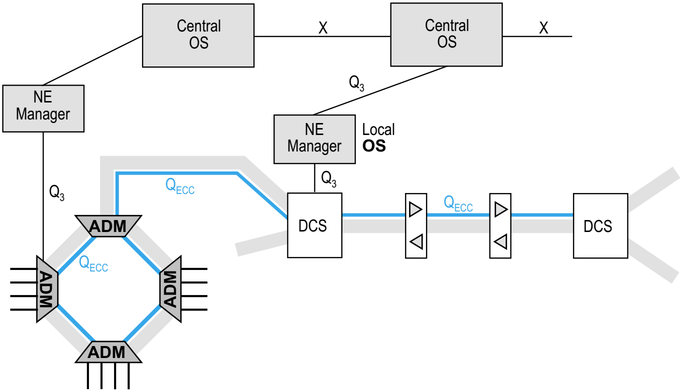
To provide these functions, TMN uses object-oriented techniques based on the open system interconnection (OSI) reference model. The TMN model comprises one manager that handles several agents. The agents in turn each handle several managed objects (MOS). The manager is included in the operating system (OS) which forms the "control center" for the network as a whole or in part. In SONET networks, the agents are located in the NEs. An MO may be a physical unit, for example a plug-in card, or multiplex section, but can also occur as a logical element such as a virtual connection.

TMN can also distinguish between logical management units. For example, one management unit operates at network level, handling individual NEs. Another management unit operates at the service level to monitor billing charges for example.

These tasks are performed in modern telecommunications networks by using the common management information protocol (CMIP). The simple network management protocol (SNMP) is often mentioned in this context and is basically a simplified form of CMIP. SNMP is mainly used in data communications, however, and cannot cope with the requirements of large telecommunications networks. The interfaces, 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.

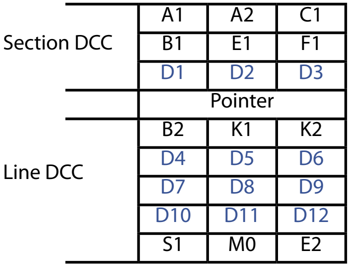
Since large quantities of data are not generally required for exchanging information in the TMN, the capacity of the embedded communication channels (ECC) or data communication channels (DCC) is sufficient when managing SONET networks. Channels D1 to D3 with a capacity of 192 kb/s (section DCC) are used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

Figure 23: TMN overlay



To distinguish the implementation in the TOH from data channels from the Q interface, the term Q_{ECC} protocol is used. Such networks are called SONET management networks (SMN) and are primarily responsible for managing NEs. SMNs can also be subdivided into SONET management sub-networks (SMS).

Figure 24: D bytes in the STS-1 TOH



SONET measurement tasks

Although trouble-free operation of all NEs should have been guaranteed by standardization on the part of various bodies (ITU, ETSI, ANSI, Telcordia), problems still arise, particularly when NEs from different sources are linked together. Transmission problems also occur at gateways between networks run by different providers.

The measurement facilities built into the system provide only an approximate location of a fault. Separate measuring equipment in contrast, is of much greater use particularly when monitoring individual channels, and more data relevant to clearing the fault can be obtained. The only areas that are covered by both network management and measurement procedures are long-term analysis and system monitoring.

Separate measuring equipment, of course, finds further application in the fields of research and development, production, and installation. These areas in particular require test equipment with widely differing specifications.

In production and installation for example, systems manufacturers configure their NEs or entire networks according to customer requirements and use measuring techniques that check everything operates as it should. The equipment is then 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 production and installation and to verify correct functioning. Such test equipment needs to be portable, robust, and capable of performing test sequences in order to reproduce repeat measurements and long-term analyses reliably and quickly.

With network providers, fault clearance and maintenance are the main areas of deployment for measuring equipment. The continuing process of network optimization is also a major area in which test equipment needs to be portable. It must also be reasonably priced, suitable for in and out-of-service measurements, and provide users with a rapid, easily interpreted display of results.

Generally speaking SONET test equipment must also be capable of fulfilling the following measurement tasks:

- Mapping analysis
- Alignment 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 the system’s in-built sensors
  - Drop and insert measurements
  - Checking network synchronization
  - Measurements on the TMN interface
- Error performance measurement:
  - Jitter and wander analysis

Some of these measurements are discussed in more detail below.

Sensor tests

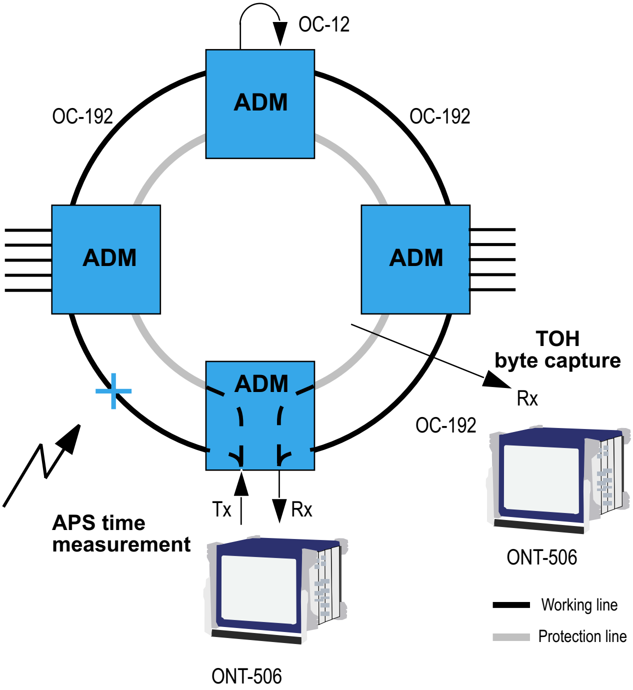
These measurements are performed in order to check the reaction of system components to defects and anomalies. Anomalies are faults such as parity errors.

Defects result in the interruption of a connection. As an example, an NE must react to an LOS alarm by sending an AIS to the subsequent NEs and transmitting an RDI signal in the return path (figure 25).

APS time measurements

A special mechanism operates in SONET networks in the event of a fault that allows the faulty link to be automatically rerouted over a back-up circuit (see APS section above). This function is controlled using overhead bytes K1 and K2. Switching over to the protection line must take place in less than 50ms. External equipment is needed to ensure this and to measure the response time that is the loss of a specific test pattern or triggering of a preset alarm when a connection is intentionally interrupted (figure 25). The measurement is important as a delayed response can result in considerable degradation in performance and even total failure of the network leading to loss of income for the network provider.

Figure 25: Checking APS response time

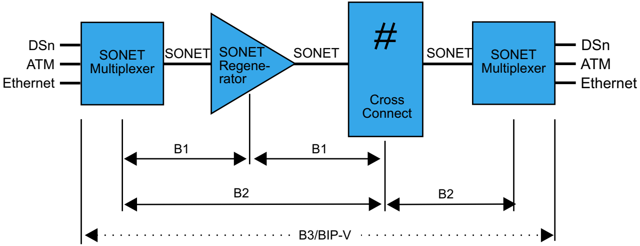


ANSI/Telcordia performance recommendations

The quality of digital links is determined with the aid of bit error ratio tests (BERT). The results of such measurements must, however, be classified in some way, not least because the quality of a transmission path is often the subject of a contract between the network provider and the telecommunications user. For this reason, an objective means of classifying a line as either “good” or “bad” is required. The American standardization bodies ANSI and Telcordia have taken up this issue in their recommendations T1.231, T1.102 and GR-253.

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 figure 26).

Figure 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.

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

Table 4: Anomalies and associated OH bytes

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 that are not SES.
- Severely errored frame second (SEFS): Seconds with OOF (LOF, LOS) in section analysis.

Derived parameter:

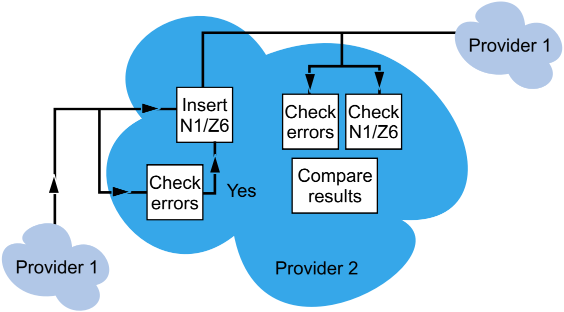
- Error-free second (EFS): A one-second time interval in which no bit errors occur.

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 and is evaluated at the start and end of the path. However, it is becoming increasingly necessary to determine the quality of individual segments of a path which might pass through the networks of different providers. 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 warrants an answer. TCM allows monitoring of the performance of path segments with the aid of the N1 and Z6 bytes in the STS-POH and VT-POH. The POH parity bytes are evaluated by the NEs. The number of errors detected is indicated to the end of the TCM using the N1 or Z6 byte. This error count is compared again with the number of parity errors detected at the end of the TCM. The difference is the number of errors occurring within the TCM.

Figure 27: Path parity check on the respective network limits; comparison using N1/Z6 bytes



Jitter measurements

The term jitter refers to phase variations in a digital signal in which 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, it is described as “wander”. Signals affected by jitter cannot be sampled accurately. In an extreme situation, this might result in misinterpretation of the input signal leading to 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 causes bit slips. The theoretical limit of correct sampling at high jitter frequencies is half the bit width. Distortion and additive noise means that the actual limit must be set much lower than this. The causes of jitter lie chiefly in the clock sources for NEs such as regenerators and add/drop multiplexers. The various types of jitter are illustrated in table 5.

Causes of Jitter

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 that occur as a result are equalized by means of a smoothed clock signal. This smoothing however is imperfect, resulting in stuffing and wait-time jitter.
Pattern jitter	Distortion in the digital signal leads to so-called intersymbol 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 diurnal temperature variations.

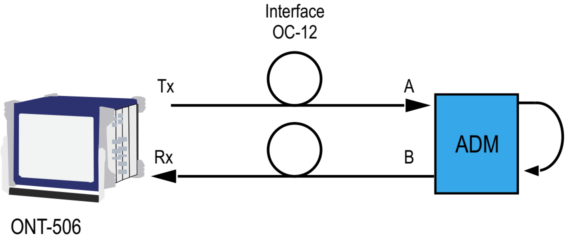
Table 5: Causes of jitter

Other causes of jitter are interference signals and phase noise. Jitter caused by interference signals is also called non-systematic jitter. Phase noise can occur 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)

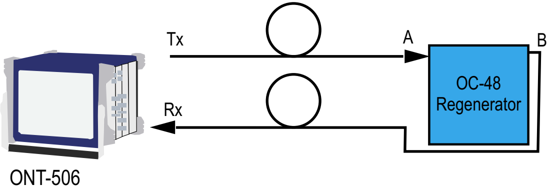
Every digital input interface must be able to tolerate a certain amount of jitter before bit errors or synchronization errors occur. The measurement is made by feeding the input of the device under test with a digital signal modulated with sinusoidal jitter from a jitter generator.



A bit error tester monitors the output of the device for bit errors and alarms which eventually occur as the jitter amplitude is increased.

Jitter transfer function (JTF)

The JTF of an NE indicates the degree to which jitter is passed on to the output.



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".

Pointer jitter

Measurement of permitted pointer jitter is performed by feeding the synchronous demultiplexer with an SONET signal containing defined sequences of pointer activity.

Combined jitter

Jitter at PDH outputs is caused by stuffing during mapping and by pointer activity.

Wander analysis

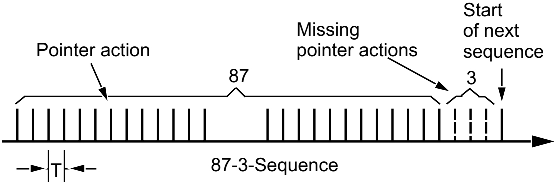
An external, high-precision reference signal is required for performing wander measurements. The phase of the signal under test is compared with the reference signal phase. The very low frequency components require appropriately long measurement times of up to 12 days.

Simulating pointer activity

If the jitter behavior of a tributary output in response to pointer activity is to be tested, pointer sequences must be used. These sequences have been defined by ANSI and Telcordia to guarantee network stability even under extreme conditions.

Pointer sequence 87-3 INC

This is a sequence of steady pointer increments where three pointer actions are omitted after a sequence of 87 actions. This kind of sequence can occur as a result of loss of synchronization in an NE and can cause very large jitter amplitudes.



Overview of current ANSI/Telcordia recommendations relevant to SONET

T1.101-1999	Synchronization interface standards for digital networks
T1.102-1993 (R2005)	Digital hierarchy – Electrical interfaces
T1.102.01-1996 (R2001)	Digital hierarchy – VT 1.5 electrical interface
T1.105-2001	SONET – Basic description including multiplex structure, rates and formats
T1.105.01-2000 (R2005)	SONET – Automatic protection
T1.105.02-2001	SONET – Payload mappings
T1.105.03-2003	SONET – Jitter and Wander at Network and Equipment Interfaces
T1.105.04-1995 (R2001)	SONET – Data communication channel (DCC) protocol and architectures
T1.105.05-2002	SONET – Tandem connection maintenance
T1.105.06-2002	SONET – Physical layer specifications
T1.105.07a-1996 (R2001)	SONET – Sub STS-1 interface rates and formats specifications
T1.105.08-2001	SONET – In-band Forward Error Correction Code Specification
T1.105.09-1996 (R2002)	SONET – Network element timing and synchronization

T1.119.02-1998 (R2004)	SONET– OAM&P-Communications-Performance Management Fragment
T1.231-2003	Digital hierarchy – Layer 1 in-service digital transmission performance monitoring
T1.245-1997 (R2003)	Directory Service for Telecommunications Management Network (TMN) and Synchronous Optical Network (SONET)
T1.261-1998 (R2004)	OAM&P - Security for TMN Management Transactions over the TMN Q3 Interface

GR253	SONET Transport System: Common Generic Criteria
GR499	Generic Requirements and Design Considerations for Fiber Distributing Frames

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 × 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 Bits
	BPS Bits per Second
	BSHR Bi-directional Self Healing Ring
	BLSR Bi-directional Line Switched Ring
C	C2 Signal label
	CAS Channel Associated Signaling
	CCM Cross Connect Multiplexing
	CMIP Common Management Information Protocol
	CSES Consecutive Severely Errored Second

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
	DSn Digital Signal
	DWDM Dense Wavelength Division Multiplexing
	DCS Digital Cross Connect
E	E1 Electrical Interface Signal 2048 kb/s
	E2 Electrical Interface Signal 8448 kb/s
	E3 Electrical Interface Signal 34368 kb/s
	E4 Electrical Interface Signal 139264 kb/s
	E1 Section layer orderwire channel
	E2 Line layer orderwire channel
	EBC Errored Block Count
	ECC Embedded Communication Channel
	ECSA Exchange Carrier Standards Association
	EDC Error Detection Code
	EFS Error Free Second
	ES Errored Second
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 HDLC High Level Data Link Control
I	IP Internet Protocol 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
	OSI Open System Interconnection
P	PDH Plesiochronous Digital Hierarchy
	PLL Phase Locked Loop
	POH Path Overhead
	POS Packet over SONET/SDH
	PPP Point-to-Point Protocol
	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
	SEP Severely Errored Period
	SES Severely Errored Second
	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	UAS Unavailable Second
	UAT Unavailable Time
	UNEQ Unequipped
	UI Unit Interval
V	V5 VT-POH byte
	VT Virtual Tributary
W	WDM Wavelength Division Multiplexing

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