G.709

The Optical Transport Network (OTN)

Executive Summary

With the growing demand for services and bandwidth and simultaneous decrease in capital budgets, the onus is now on operators to use their existing fiber networks to satisfy the market needs. Since the 1980s, SONET/SDH has met these needs by providing protection and performance monitoring whilst supporting a flexible and transparent mix of traffic protocols including IP, Fiber Channel, Ethernet and GFP. Whilst deployment of Dense Wavelength Division Multiplex (DWDM) networks during the following decade served to increase existing fiber bandwidth, it severely lacked the protection and management capabilities inherent in SONET/SDH technology. DWDM deployment also came with a completely new set of Network Elements (NE) including optical amplifiers, switches, multiplexers, demultiplexers, all of which introduced a sub layer into the network warranting constant monitoring to guarantee fault free traffic.

The aim of the Optical Transport Network (OTN) is to combine the benefits of SONET/SDH technology with the bandwidth expandability of DWDM. In short, OTNs will apply the Operations, Administration, Maintenance and Provisioning (OAM&P) functionality of SONET/SDH, to DWDM optical networks.
This newly developed OTN is specified in ITU-T G.709 *Network Node Interface for the Optical Transport Network (OTN)*. This recommendation - sometimes referred to as Digital Wrapper (DW) - takes single wavelength SONET/SDH technology a step further enabling transparent, wavelength manageable multi-wavelength networks. Forward Error Correction (FEC) adds an additional feature to the OTN by offering the potential for network operators to reduce the number of regenerators used leading to reduced network costs.

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The OTN Vision– Properties of the OTN

The aim of the OTN is to enable the multi service transport of packet based data and legacy traffic, whilst DW technology accommodates non intrusive management and monitoring of each optical channel assigned to a particular wavelength. The "wrapped" overhead (OH) would therefore make it possible to manage and control client signal information. *Figure 1* illustrates how the OTNs management capabilities are achieved with the addition of OH at several positions during the transport of the client signal.
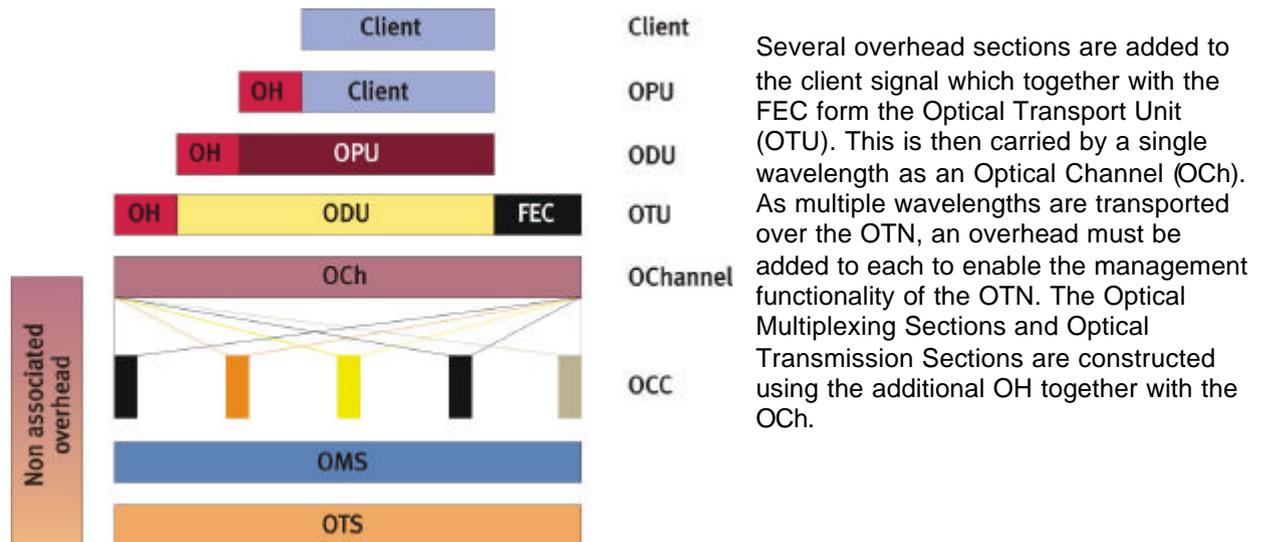

Several overhead sections are added to the client signal which together with the FEC form the Optical Transport Unit (OTU). This is then carried by a single wavelength as an Optical Channel (OCh). As multiple wavelengths are transported over the OTN, an overhead must be added to each to enable the management functionality of the OTN. The Optical Multiplexing Sections and Optical Transmission Sections are constructed using the additional OH together with the OCh.

Figure1: Basic transport structure of an OTN

OTNs present a number of advantages to network operators including:
– protocol transparency
– backward compatibility for existing protocols
– allowance of FEC coding
– reduction in 3R regeneration (through flexible optical network designs)

The last point is of particular significance as it minimizes network complexity which leads to reduced costs.
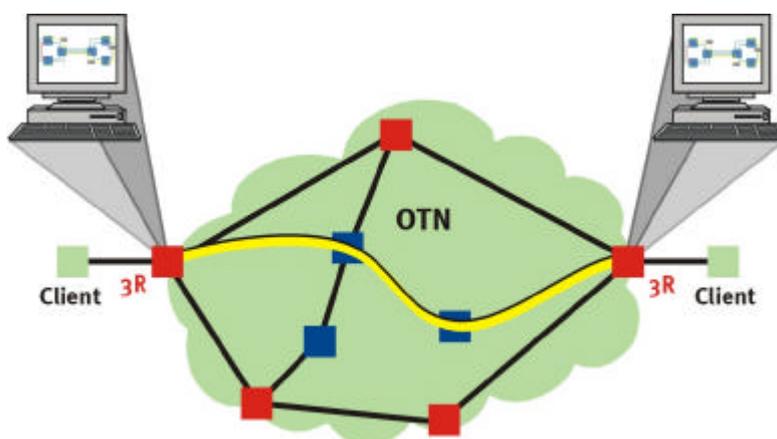

Figure 2 illustrates 3R regeneration which occurs on the OTN ingress Inter-domain Interface (IrDI). The transport through the network may take place solely in the optical domain. A point to note however is that at the present time no management capabilities exist for dealing with optical signals which have not been converted to digital format. In contrast to the transparent network, the opaque network performs a 3R regeneration at each node in the network

Figure 2: OTN network

ITU-T G.709 standards for OTNs

The ITU-T G.709 standard, *Network Node Interface for the Optical Transport Network (OTN),* defines the OTN IrDI (inter-domain interface) in the following ways:

– functionality of the overhead in preparing the multi wavelength optical network
– Optical Transport Unit framing structure
– bit rates and formats permitted for mapping of the clients

Two types of interface are described in the ITU-T G.872 recommendation *Architecture of the Optical Transport Networks* , the locations of which are illustrated in *figure 3.*
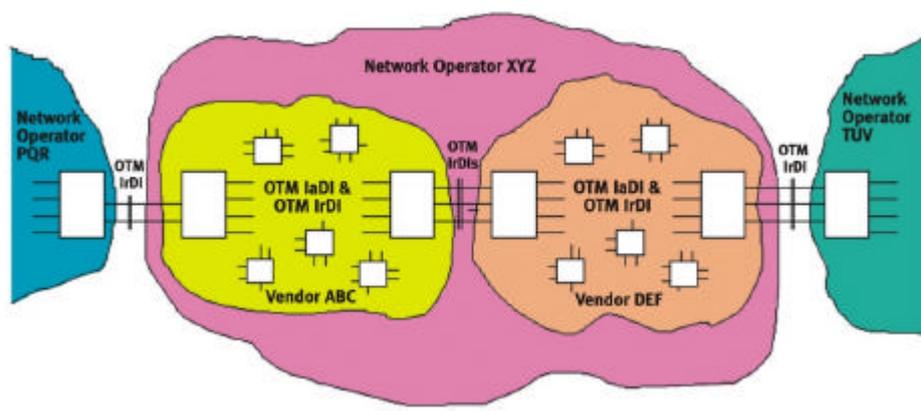
Figure 3. Network interfaces as defined in ITU-T G.872

Inter-Domain Interfaces (IrDI)

These define:
– the location between the networks of two operators
– the location between the sub-networks of two vendors in the same operator domain
– the location within the sub-network of one vendor

Intra-Domain Interfaces (IaDI)

This defines:
– the location between the equipment of an individual manufacturer's sub-network

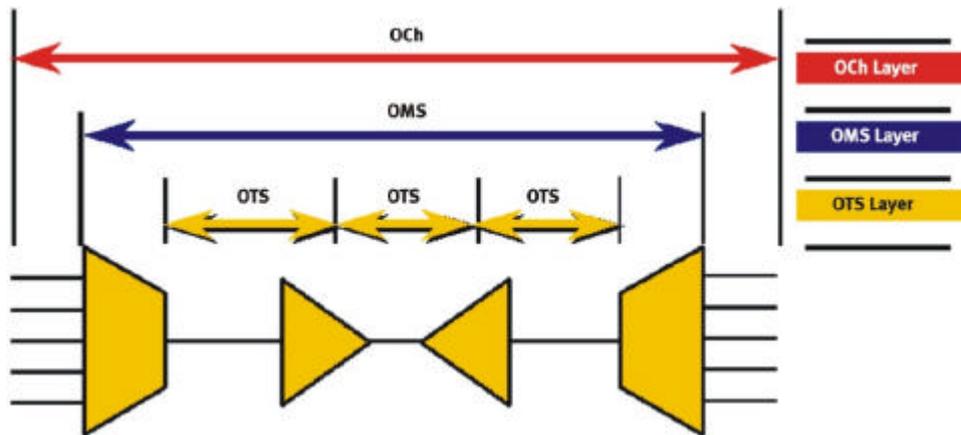As with SONET/SDH, the OTN has a layered structure design.

Figure 4. OTN layer structure

The basic OTN layers are visible in the OTN transport structure and consist of the Optical Channel (OCh), Optical Multiplex Section (OMS) and Optical Transmission Section (OTS) as shown in *figure 4*. Transport of a client signal in the OTN follows the procedure outlined below:

– OH is added to the client signal to form the Optical channel Payload Unit (OPU)
– OH is then added to the OPU thus forming the Optical channel Data Unit (ODU)
– additional OH plus FEC are added to form the Optical channel Transport Unit (OTU)
– adding further OH creates an OCh which is carried by one color
– additional OH may be added to the OCh to enable the management of multiple colors in the OTN. The OMS and the OTS are then constructed
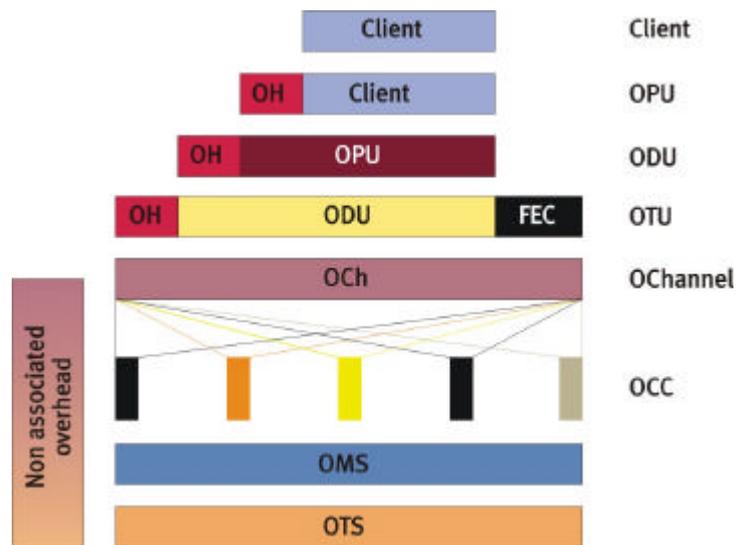

Figure 5. Basic OTN transport structure

The result is an optical channel (OCh) comprising an OH section, a client signal and a FEC segment.

Figure 6: Optical channel structure consisting of OH bytes, client and FEC.

The OCh OH which offers the OTN management functionality, contains 4 substructures: the Optical channel Payload Unit (OPU), Optical channel Data Unit (ODU), Optical channel Transport Unit (OTU) and Frame Alignment Signal (FAS).

The **client signal** -or actual payload to be transported - could be of any existing protocol i.e.; SONET/SDH, GFP, IP, GbE.

Figure 7: Client in an Optical Channel

The **Optical channel Payload Unit** (OPU) OH is added to the OPU payload and is used to support the various client signals. It regulates the mapping of the many client signals and provides information on the type of signal transported. The ITU-T G.709 currently supports asynchronous as well as synchronous mappings of client signals into the payload.
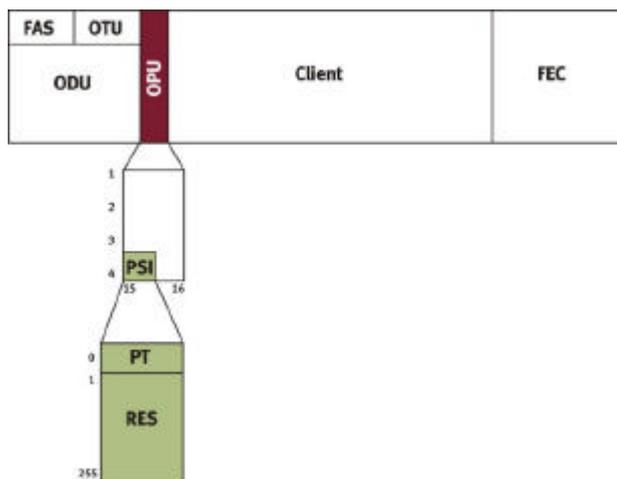
The OPU OH consists of the Payload Structure Indentifier (PSI) which includes the Payload Type (PT) and overhead bits associated with the mapping of client signals into the payload, like for example, the justification bits required for asynchronous mappings. The OPU OH is then terminated at the point where the OPU is assembled and disassembled.

Figure 8: Overhead of OPU

The OPU **Payload Structure Identifier (PSI)** field transports a 256-byte message aligned with the ODU multi frame. PSI0 contains the payload type (PT) identifying the payload being transported. The **OPU Payload Type (PT)** is a single byte defined within the PSI to indicate the composition of the OPU signal, or in other words, the type of payload being carried in the OPU.
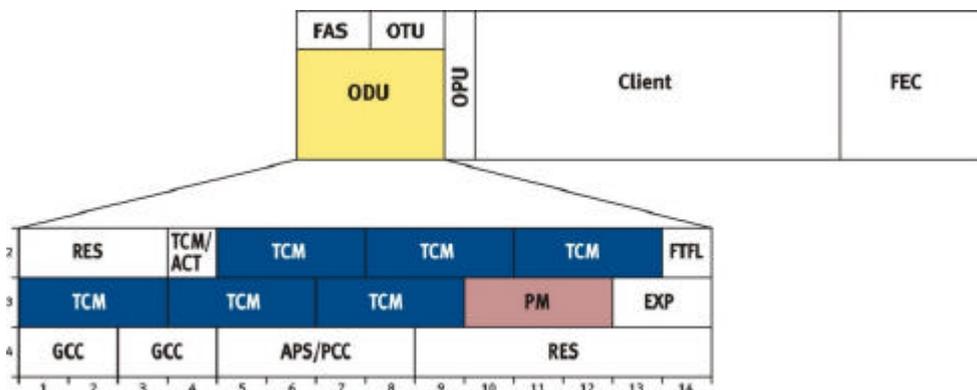

Figure 9: Overhead structure of ODU

The **Optical channel Data Unit (ODU) OH** allows the user to support Tandem Connection Monitoring (TCM), Path Monitoring (PM) and APS. End-to-end path supervision and client adaptation via the OPU (as described previously) are also made possible.

The ODU OH provides two important overheads: the Path Monitoring (PM) overhead and the TCM overhead.

The **ODU Path Monitoring OH** enables the monitoring of particular sections within the network as well as fault location in the network via the overhead bytes described in the PM OH.

The PM OH is configured in row 3, columns 10 to 12 to support path monitoring. The PM field structure contains the following sub fields:
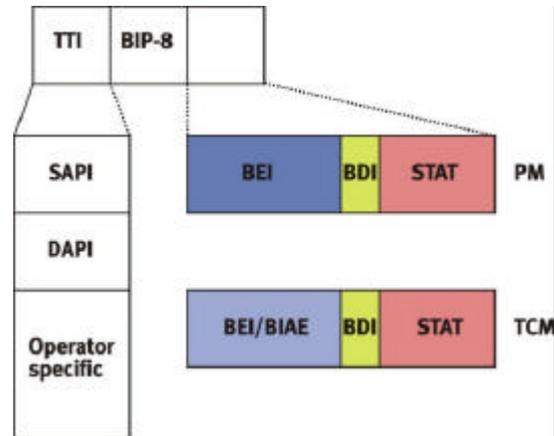

Figure 10: TCM and PM overhead structures

- Trail Trace Identifier (TTI)
  The TTI is similar to the J0 byte in SONET/SDH. It is used to identify the signal from the source to the destination within the network. The TTI contains the so called Access Point Identifiers (API) which are used to specify the Source Access Point Identifier (SAPI) and Destination Access Point Identifier (DAPI). The APIs contain information regarding the country of origin, network operator and administrative details.

– Bit Interleaved Parity (BIP-8)
  This is one byte which is used for Error Detection. The BIP-8 byte provides a bit interleaved parity – 8 code. The BIP-8 is computed over the whole OPU and inserted into the BIP-8 SM two frames later.

– Backward Defect Indication (BDI)
  This is a single bit conveys information regarding signal failure in the upstream direction.

– Backward Error Indication (BEI) and Backward Incoming Alignment Error (BIAE)
  These signals carry information on interleaved-bit blocks detected in error in the upstream direction. They are also used to convey incoming alignment errors (IAE) in the upstream direction.

– Status bits for indication of maintenance signal (STAT)
  These three bits indicate the presence of maintenance signals.

ODU Tandem Connection Monitoring OH

One particular function implemented in SONET/SDH networks is Tandem Connection Monitoring (TCM), a functionality which enables signal management across multiple networks. Hierarchical error checking using the parity bytes is another function which can be performed. In addition to this, G.709 also allows for signal management functions such as those found in wholesale wavelength services for example.

The TCM OH bytes are defined in the overhead in row 2, columns 5 to 13 as well as in row 3, columns 1 to 9 in the ODU overhead. Each TCM field contains the sub fields - as already described under *Path Monitoring* – with additional BIAE. The TCM functionality implemented in the OTN is capable of

monitoring up to 6 tandem connections independently. TCM allows for the nesting and overlapping of ODU monitoring connections.
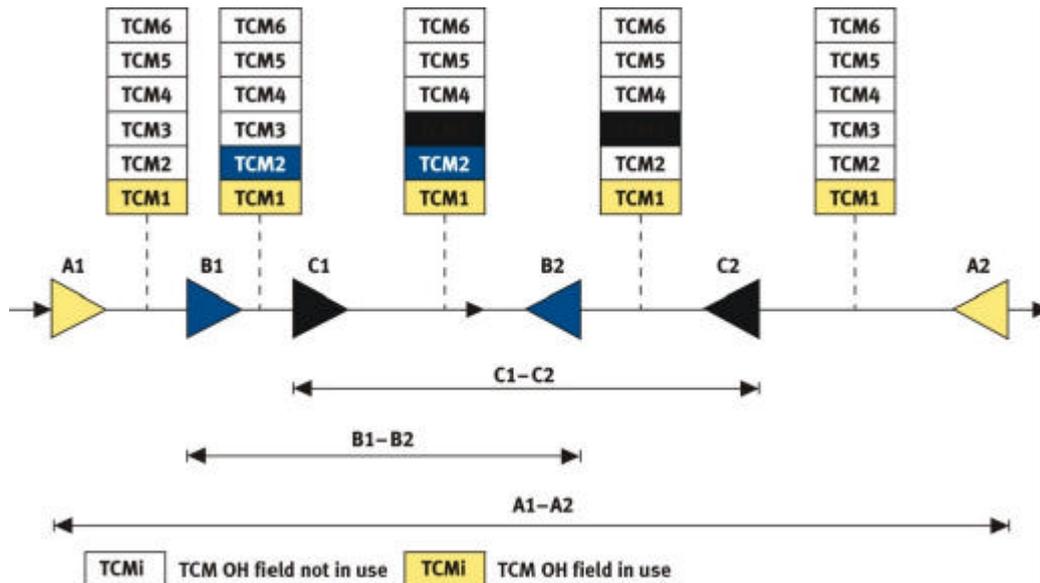

Figure 11: Possible TCM structure in an OTN.

As illustrated in figure 11, monitoring is possible between A1-A2, B1-B2 and C1-C2 in nested mode. With B1-B2, this is only possible in cascaded mode. These functionalities could potentially be used by carriers in maintaining their own Service Level Agreements within their networks.

The additional overhead bytes of the ODU OH are described below.

– RES
These bytes are reserved for future international standardization. All bytes are set to zero as they are currently not in use.

– TCM/ACT
This one byte field is used for the activation and deactivation of the TCM fields. At present, these fields are still being studied.

– EXP
These bytes are reserved for further experimental use.

– General communication channels (GCC1, GCC2)
These two fields allow communication between two network elements with access to the ODU frame structure.

– Automatic Protection Switching and Protection Communication Channel (APS/PCC)
APS switching on one or more levels is made possible.

– Fault Type and Fault Location channel (FTFL)-
One byte in the ODU OH is reserved for the FTFL message. This byte provides fault status information including information regarding type and location of the fault. The FTFL is related to the TCM span.
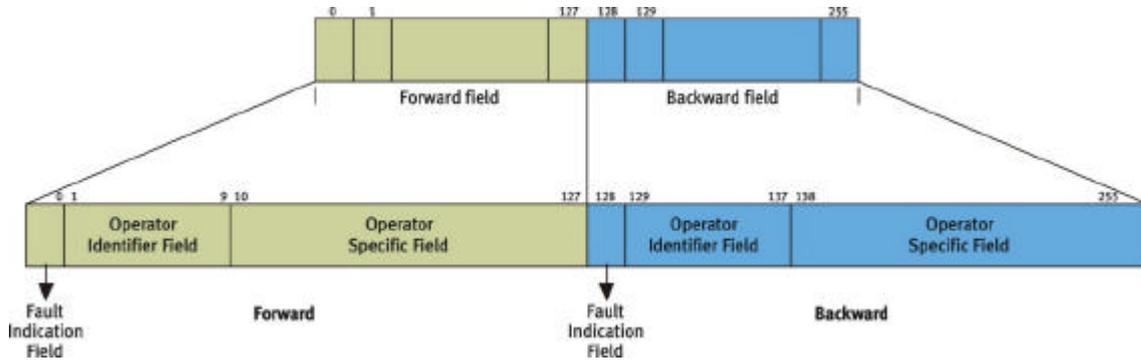
Figure 12: Structure of the FTFL field with its corresponding substructure

The sub-structure contains; forward and backward fault type indication fields, forward/backward operator identifier fields and forward/backward operator specific fields which perform the following functions:

The Fault Type Indication Field

The codes specified so far indicate the following situations:

– No Fault

– Signal Fail

– Signal Degrade

The additional bytes in the FTFL message field are reserved for future international standardization

Operator Identifier Field

This field specifies the geographic origin of the operator and includes a national segment field

Operator Specific Field

These fields are not standardized by the ITU-T G.709 recommendations

Optical channel Transport Unit OH and Frame Alignment

The OTU is used in the OTN to support transport via one or more optical channel connections. It also specifies both Frame Alignment and FEC.
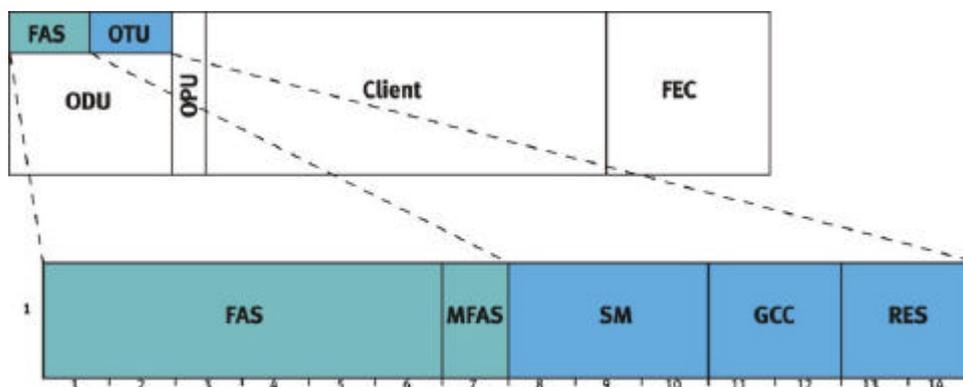

Figure 13: Frame Alignment and OTU OH structure

The **Frame Alignment OH** is part of the OTU OH. It is situated in row 1, columns 1 to 6 of the OTU in which a Frame Alignment Signal (FAS) is defined (*figure 13*). As the OTU and ODU frames could span multiple OTU frames, a multi framed, structured overhead signal is defined. The Multi Frame Alignment Signal (MFAS) is defined in row 1, column 7 of the OTU/ODU overhead. The value of the MFAS byte is incremented with each OTU/ODU frame
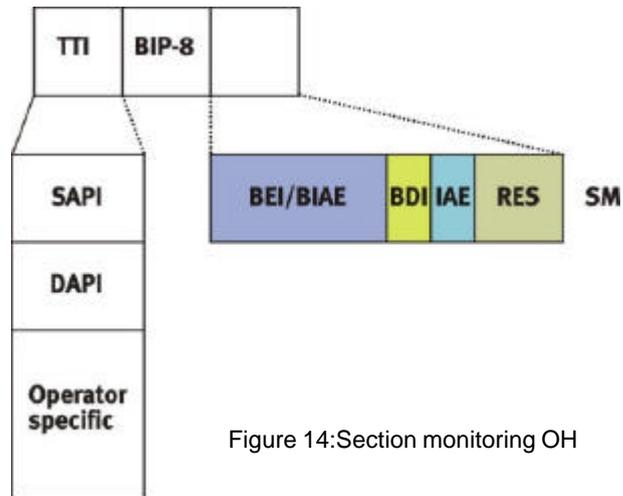

Figure 14:Section monitoring OH

The **Section Monitoring OH** consists of the sub fields as described for the path monitoring OH, with exception to the Incoming Alignment Error (IAE) bit. This bit allows the ingress point to inform the egress point that an alignment error in the incoming signal has been detected. IAE is set to "1" when an error occurs, otherwise it is set to "0".

General Communication Channel 0 (GCC0) is used as a communication channel between OTU termination points.

Forward Error Correction (FEC)

In conjunction with the OCh OH of the digital wrapper "envelope", additional bandwidth – in this case FEC -– is added. The implemented algorithm/FEC enables the correction and detection of errors in an optical link.

Figure 15: FEC structure of the OCh

FEC is already widely used by under sea cable operators in various designs. There are also several algorithms/codes which can be used to perform the error correction.

The FEC implementation defined in the G.709 recommendation uses the so called Reed-Solomon code RS(255/239). Here, an OTU row is split into 16 sub rows each consisting of 255 bytes. The sub-rows are formed byte interleaved, meaning that the first sub row consists of both the first OH byte and the first payload byte. The first FEC byte is inserted into byte 240 of the first sub-row. This is true for all 16 sub-rows.
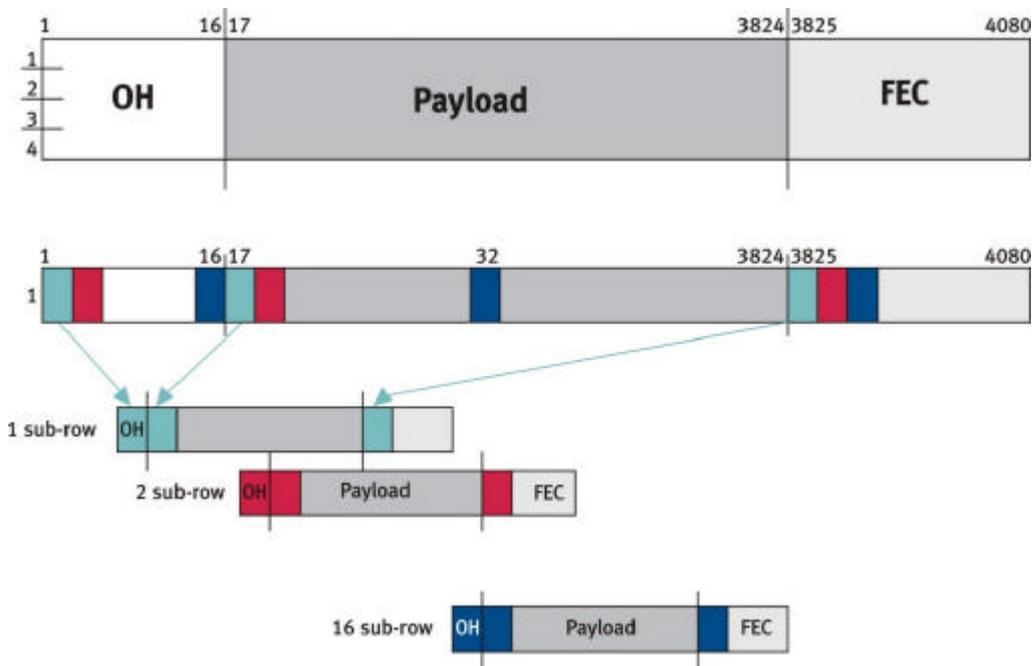
Figure 16: Illustration of Reed-Solomon coding in the G.709 recommendation

Of these 255 bytes, 239 are used to calculate the FEC parity check, the result of which is transmitted in bytes 240 to 255 of the same sub row.
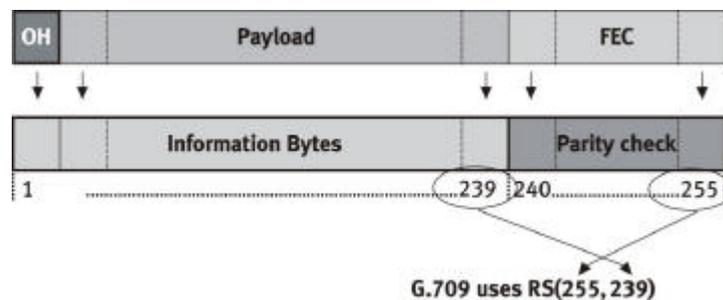

Figure 17: Forming of parity check

The Reed-Solomon code detects 16 bit errors or corrects 8 bit errors in a sub row. The FEC RS(255,239) is specified for the fully standardized IrDI interface. Other OTUkV interfaces (eg; IaDI) – which are only functionally standardized – may use other FEC codes.

The case for using FEC in optical networks

FEC enables the detection and correction of bit errors caused by physical impairments in the transmission medium. These impairments are categorized into linear (attenuation, noise and dispersion) and nonlinear (four wave mixing, self phase modulation, cross phase modulation) effects.
When FEC is used in a network link, the network operator can accept a lower quality signal in the link so that potential errors can be corrected.
The chart below illustrates the effect of an increase in signal quality in three cases. In one case, no FEC is used. In the remaining two cases, FEC is utilized but with different coding algorithms.
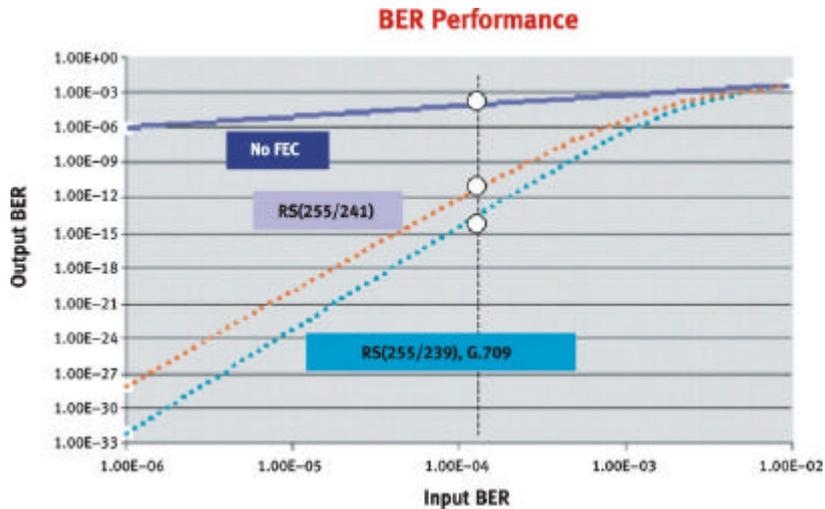
Figure 18: Effect of using FEC with various algorithms.

An input Bit Error Rate (BER) of approximately 10^{-4} can in this instance, be improved to an output BER of about 10^{-15} in the best case scenario, The output BER however shows no improvement when an FEC algorithm is not used.

The benefits of FEC in optical networks

The potential improvement in signal quality in an optical link offers many advantages including:

– gain in power level of approximately 5dB. This is achieved when using 7% FEC. (correlating to a link expansion of approximately 20km).

– reduction in the use of 3R regenerators. This is made possible by increasing the distance between links.

– use of existing 2.5Gbit links to transport 10Gbit traffic. This has been attempted and could be made possible given that FEC allows for the correction of the lower signal quality

– early warning capabilities. Some Network Elements (NE) monitor corrected errors in links. This parameter could in turn be used as an early warning tool whereby the amount of errors corrected in a link could signify the weakening of a component in the link itself.

Once the optical channel is formed, additional non associated OH is added to individual OCh wavelengths, which then form the Optical Multiplexing Sections (OMS) and Optical Transmission Sections (OTS).
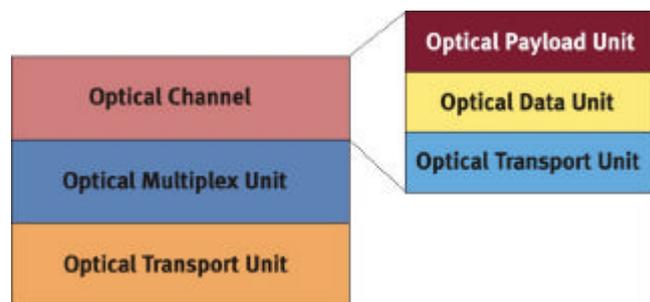

Figure 19: OCh substructure and basic OTN structure.

In the **Optical Multiplex Section (OMS)** layer, both the OMS payload and non associated overhead (OMS OH) are transported. The OMS payload consists of multiplexed OChs. The OMS-OH, although undefined at this point, is intended to support the connection monitoring and assist service providers in troubleshooting and fault isolation in the OTN.

The **Optical Transmission Section (OTS)** layer transports the OTS payload as well as the OTS Overhead (OTS-OH). Similar to the OMS, the OTS transports the optically multiplexed sections described above. The OTS OH - although not fully defined - is used for maintenance and operational functions. The OTS layer allows the network operator to perform monitoring and maintenance tasks between the NEs which include; OADMs, multiplexers, demultiplexers and optical switches.

FEC measuring applications

The OTN provides extensive OAM&P functionality for multiple wavelengths and thus requires an extensive overhead. To guarantee bandwidth availability and quality of the transmission in the network, the overhead bytes need to be monitored. In addition to monitoring the status of these overhead bytes, the system needs to be checked under stress. This procedure executed mainly by introducing alarms and errors into the system and then measuring their effect on the transmission.

The DW technology and OTN implemented FEC are relatively new technologies offering related applications for use in R&D. Measurement applications in production and installation are already either in use or planned for the near future.

Tests in R&D, production and installation are mostly functional and cover:

– signal integrity testing (optical power, ability of the DUT to synchronize on the frame, and further parameters)

– test of maintenance signals – alarm testing (eg; LOS, AIS, etc.)

– error insertion in the test signal

– mapping testing of the OTUk (eg; mapping of a SONET/SDH structure into the OTUk)

– multiplexing testing of the OTUk (eg; multiplexing of an ODM1 into an ODU2)

– G.709 OH testing (eg; test of section monitoring, path monitoring and FTFL)

– interoperability, in which TCM testing is required

– FEC error testing

– stimulation of Network Elements with anomalies (eg; alarms and errors)

Stimulus testing

A stimulus is sent to the DUT and the return signal monitored by the measuring equipment. The signal received must correlate with the stimulus. Should the two signals not match, the user then receives information on the DUT allowing further investigations to be carried out. Possible stimuli could include the standard OTN errors and alarms as defined in G.709 recommendations.
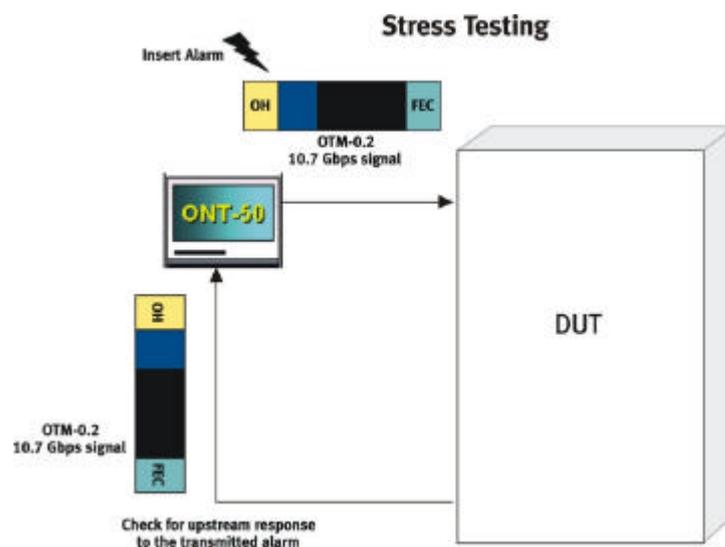

Figure 20: Setup for stimulus testing

Mapping and demapping of client signals

The OTNs framing structure makes the mapping of a variety of traffic types into OPUs possible. This includes for example; SONET/SDH (STM-256) into OPU3, mapping of ATM cells into the OPU and the mapping of Generic Frame Procedure (GFP) frames into the OPU. Rate differences between the client and the OPU of course need to be adjusted. This test is also extremely useful as either synchronous or asynchronous mappings are required for the various client mappings. In order to perform this measurement, a signal with varying range is transmitted then mapped into the OPU by the DUT. The receiver can then detect if the client has been properly mapped into the OPU.
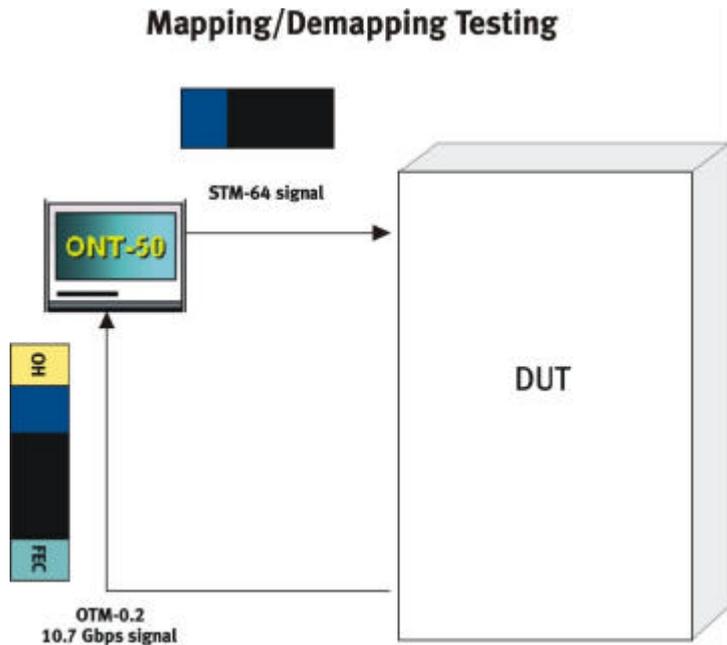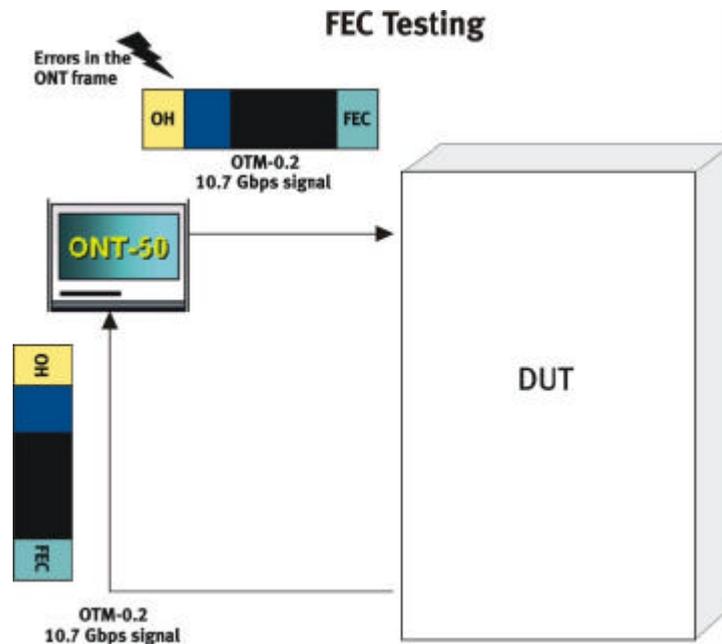

Figure 21: Mapping and demapping testing

FEC Testing

Figure 22: Setup for FEC testing

In order to carry out full FEC testing, an error is inserted into the OCh and is then transmitted through an OTN NE. At the receiving end, the OCh is checked to determine whether the error was corrected by the DUT. This test is performed by inserting varying numbers of errors and allowing the user in turn to check the error correcting capability of their NE. If the number of inserted errors exceeds the correction capability of the NE, the measuring equipment will reflect this as an uncorrectable error or errors.

The future of OTN

The OTN is intended to provide robust management features to support the high bandwidth in OTNs. The OTN delivers management functionality to DWDM networks, meaning that it is capable of managing multiple colors - a function comparable to the effect of SONET/SDH on single wavelengths.

The major advantage of the OTN is its full backward compatibility which makes it possible to build on the existing management functionalities available with SONET/SDH. In addition to this, full transparency of existing communication protocols such as IP, PoS and GFP is also provided.

The OTN and in particular the implementation of FEC, enables network operators to operate their existing networks both efficiently and economically. Although the G.709 standard describes the basic frame structure and management fields, the network management and the connection setup of optical links in the optical control plane are yet to be finalized.

Abbreviations

General Abbreviations

3R	Reamplify – Reshape - Retime
ATM	Asynchronous Transfer Mode
DUT	Device Under Test
DWDM	Dense Wavelength Division Multiplexing
FEC	Forward Error Correction
GbE	Gigabit Ethernet
GFP	Generic Frame Procedure
IaDI	Intra-domain Interface
IrDI	Inter-domain Interface
IP	Internet Protocol
NE	Network Element
OAM&P	Operations, Administration, Maintenance & Provisioning
OTN	Optical Transport Network
SDH	Synchronous Digital Hierarchy
SONET	Synchronous Optical Network

Abbreviations regarding the OTN

APS	Automatic Protection Switching
BDI	Backward Defect Indication
BEI	Backward Error Indication
BIP-8	Bit Interleaved Parity-8
DW	Digital Wrapper
EXP	Experimental
FAS	Frame Alignment Signal
FTFL	Fault Type and Fault Location
GCC	General Communication Channel
IAE	Incoming Alignment Error
MFAS	Multi frame Alignment Signal
OADM	Optical Add Drop Multiplexer
OCh	Optical Channel
ODU	Optical channel Data Unit
OH	Overhead
OPU	Optical channel Payload Unit
OMS	Optical Multiplexing Section
OTM	Optical Transmission Module
OTU	Optical channel Transport Unit
OTUk	Completely standardized Optical Channel Transport Unit-k
OTS	Optical Transmission Section
PCC	Protection Communication Channel
PM	Path Monitoring
PSI	Payload Structure Identifier
PT	Payload Type
RS	Reed-Solomon
RES	Reserved
SM	Section Monitoring
STAT	Status
TCM	Tandem Connection Monitoring
TTI	Trail Trace Identifier

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