

A G.709 Optical Transport Network Tutorial

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Introduction

The amount of data traffic relative to voice traffic on optical networks and the total traffic volume continues to increase.¹ These factors are driving emerging, flexible technologies to supplement the mature, voice-optimized synchronous optical network(ing)/synchronous digital hierarchy (SONET/SDH) transport infrastructure and to help manage network complexity. At the edge of the network, where data and voice combine in a common infrastructure, new data-centric applications have emerged. Examples of these new applications include dynamic bandwidth settings provided by the combination of virtual concatenation (VCat), which provides flexible bandwidth groupings for SONET/SDH, Link Capacity Adjustment Scheme (LCAS), and generic framing procedures (GFP), which provides a protocol-agnostic frame container.^{2,3,4} In the transport core, bandwidth requirements spawned the creation of the optical transport network (OTN) described in general terms in International Telecommunications Union-Telecom (ITU-T) G.872.⁵ ITU-T G.709 provides the network interface definitions.⁶

G.709 improves transport network performance and facilitates the evolution to higher backbone bandwidths. The G.709 OTN frame includes transport overhead that provides operation, administration, and maintenance (OAM) capabilities and forward error correction (FEC). The FEC helps reduce the number of transmission errors on noisy links, which enables the deployment of longer optical spans. This tutorial focuses on the digital applications of G.709.

Interfaces and Payload

G.709 defines standard interfaces and rates. These rates have been derived from the existing SONET/SDH rates where the G.709 overhead and FEC information have been taken into account. The resulting interfaces thus operate at line rates, roughly 7 percent higher, than the corresponding SONET/SDH that becomes the OTN payload. Table 1 lists the G.709 line rates and the matching SONET/SDH interfaces. An additional interface type, which is not part of the G.709 recommendation, applies to 10 Gigabit Ethernet local area network (LAN) clients. In this case, the same overhead structure and FEC is applied resulting in a line rate of 11.095 Gbps.

G.709 Interface	Line Rate (Gbps)	Corresponding SONET/SDH Rate	Line Rate (Gbps)
OTU1	2.666	OC-48/STM-16	2.488
OTU2	10.709	OC-192/STM-64	9.953
OTU3	43.018	OC-768/STM-256	39.813

Table 1 G.709 line rates and matching SONET/SDH interfaces

Figure 1 illustrates the three parts that constitute the G.709 OTN frame; namely the overhead, the payload, and the FEC. No direct correlation exists between the size of a G.709 frame and that of a SONET/SDH frame. For example, transmitting a single OC-192 frame takes about 11 OTU2 frames. The SONET/SDH payload clients, also referred to as constant bit rate (CBR), are accompanied by stuff bytes amounting to 64 and 128 per frame in the case of OTU2 and OTU3, respectively. These additional bytes leave room to support the multiplexing of multiple G.709 lower transmission rate signals. For example, four individual OTU1 signals, with their FEC stripped and minor overhead modifications, may be combined and interleaved into the payload of an OTU2 frame. The OTN is protocol agnostic as it supports payload types other than SONET/SDH and multiplexed G.709 signals. More specifically, native data protocols such as Asynchronous Transfer Mode (ATM) and GFP can be mapped directly into the payload area of the G.709 frame.

Though the initial development efforts focus on SONET/SDH clients, G.709 also considers the management of optical wavelengths for wavelength division multiplexing (WDM). Presently, simple wavelength identification can be provided in the existing G.709 overhead. The implementation of additional dedicated overhead for optical channels remains for future standardization.

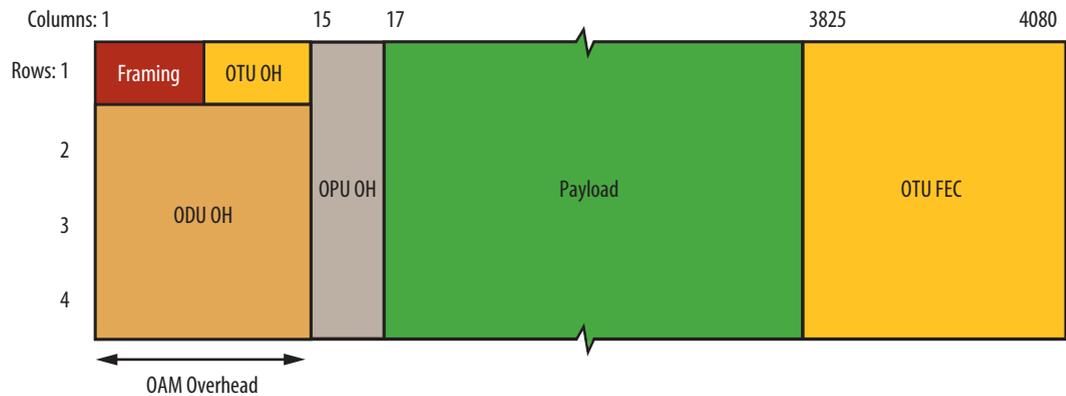


Figure 1 Three parts of a G.709 OTN frame

Forward Error Correction

FEC serves as one of the primary justifications behind G.709. It uses a Reed-Solomon (RS) code to produce redundant information that gets concatenated with the signal to be transmitted. The receiving interface uses the additional information to help with the identification and correction of, transmission errors. The RS encoding was chosen because of its low complexity, relatively high error correction capability, and low error burst sensitivity.

The G.709 FEC separates the frame data into 16 data streams, where up to 8 errored bytes can be corrected per stream, where each row is split into sub-rows, as illustrated in Figure 2. The protocol uses one overhead byte and 238 data bytes to compute 16 parity bytes to form 255 byte blocks—the RS(255,239) algorithm

Two key advantages are achieved by interleaving the information. First, the encoding rate of each stream is reduced relative to the line transmission rate and second, it reduces the sensitivity to bursts of errors. The interleaving combined with the inherent correction strength of the RS(255,239) algorithm enables the correction of transmission bursts of up to 128 consecutive errored bytes. As a result, the contiguous burst error correcting capability of G.709 is enhanced 16 times above the capacity of the RS(255,239) algorithm.

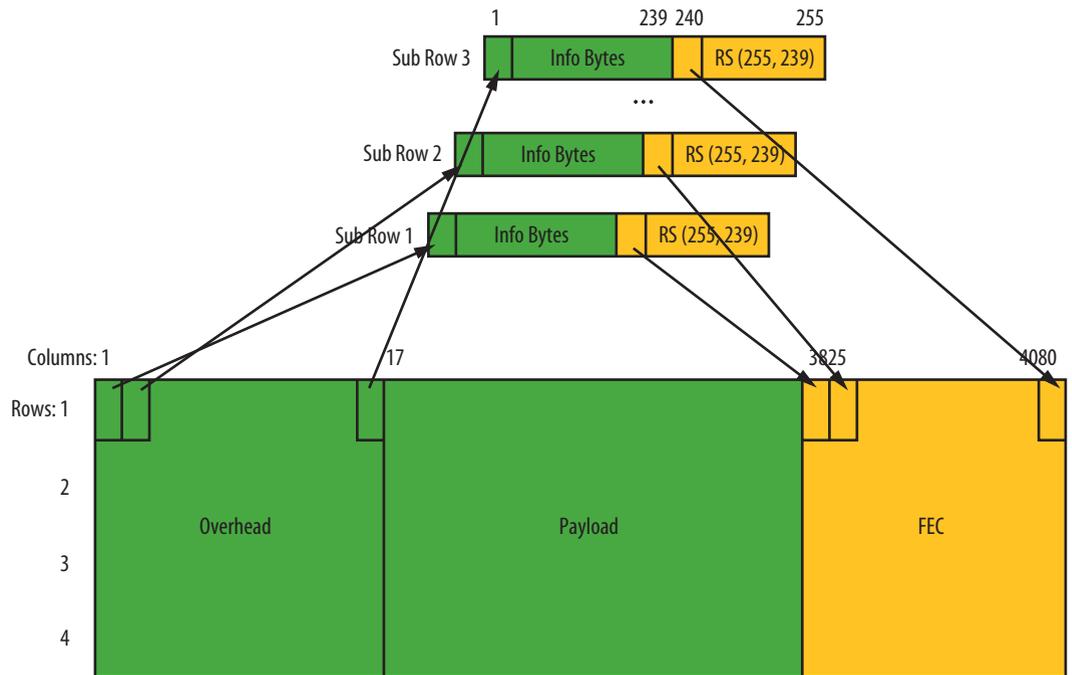


Figure 2 G.709 FEC separates from data into 16 data streams with each row split into sub-rows

Figure 3 illustrates the coding gain achieved with FEC relative to the bit error rate (BER). At high BER, the effectiveness of the FEC decreases relative to a signal without FEC. This effectiveness is quantified using the coding gain, which is described as the power decrease required that maintains the same BER as that achieved without FEC encoding. At low BER, such as 10^{-12} or 1 errored bit per terabit, G.709 achieves around 5.4 dB of optical coding gain.^{7,8} Actually, this results in longer optical spans using the same optical launch power. *FEC serves as a warning tool for degrading signals, because increased numbers of corrected symbols provides an indication of a deteriorating link.* These signs are often present before the detection of system faults or alarms, which are discussed later. G.709 supports the option to turn FEC off in, resulting in the FEC field to be filled with zeroes.

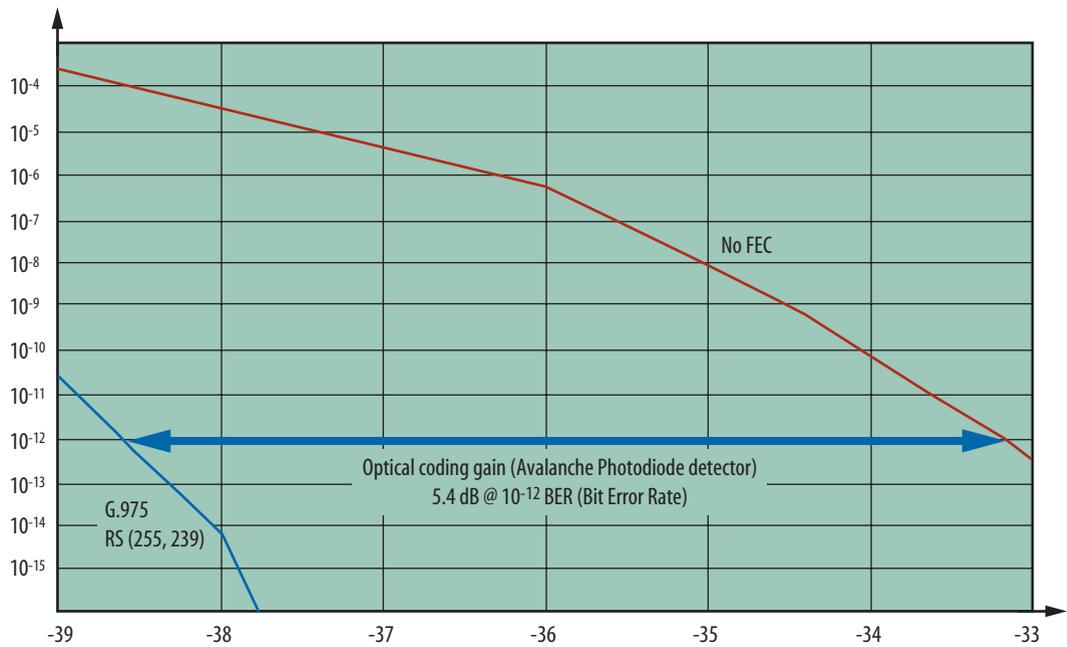


Figure 3 Coding gain achieved with FEC relative to BER

Overhead

Figure 1 showed previously that the OAM overhead has three parts: the Optical channel Transport Unit (OTU), Optical channel Data Unit (ODU), and Optical channel Payload Unit (OPU). The OTU structure, which includes the FEC, provides supervisory functions and conditions the signal for transport between optical channel termination points, where re-timing, reshaping, and regeneration occurs. The ODU provides end-to-end path supervision and supports tandem connection monitoring, while the OPU supports the adaptation of client signals for transport over an optical channel. Figure 4 provides an example of OTU, ODU, and OPU termination points in an OTN network.

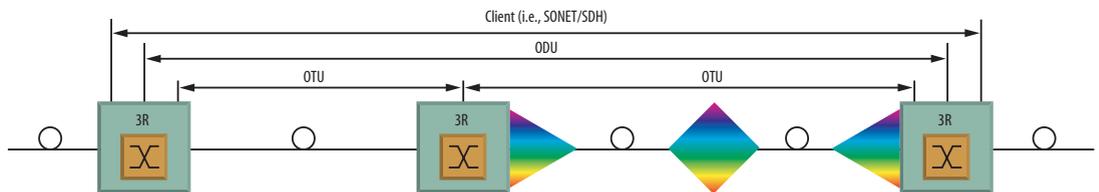


Figure 4 OTU, ODU, and OPU termination points in an OTN network

Figure 5 illustrates the framing bytes and the non-FEC portion of the OTU. In transmission systems, the framing bytes delineate G.709 frames to determine where frames start and end. Two functionally distinct framing fields exist: the frame alignment signal (FAS) bytes contain a static value of '0xF6F6F62828', while the multiframe alignment signal (MFAS) continuously increments frame after frame from 0 to 255. This system is useful in multi-frame structures, where the full meaning of a message is determined after collecting information over a fixed period covering 64 or 256 frames. The FAS and MFAS bytes are not scrambled, unlike the rest of the OTU structure. Scrambling ensures sufficient bit state transitions for clock recovery purposes and reduces the likelihood of FAS byte duplication.

In the OTU, the trail trace identifier (TTI) byte, which is part of the Section Monitoring (SM) overhead, provides an example of a multi-frame signal. It contains information on network elements in the form of source (SAPI) and destination access point identifiers (DAPI). In addition, the SM has a bit interleaved parity (BIP)-8 field and a byte for alarm signals, which are described more fully in the Fault and Alarms section. The OTU also contains the General Communications Channel field (GCC0) which resembles the Data Communications Channel (DCC) from SONET/SDH. Although the GCC function is currently undefined, it likely will be used for functions such as network management⁹ or control plane signaling for a protocol such as Generic Multi-Protocol Label Switching (G-MPLS).¹⁰ The reserved (RES) fields found throughout the overhead are allocated for future use.

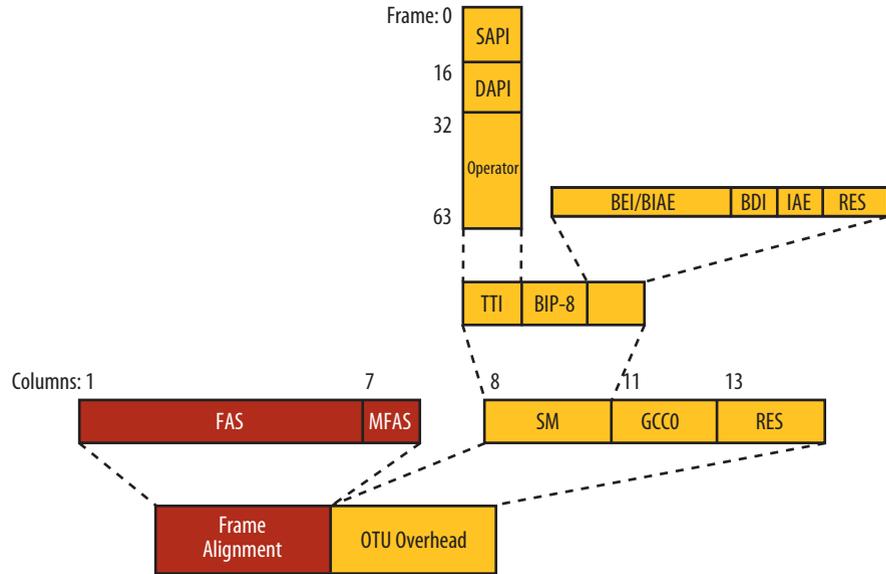


Figure 5 Framing bytes and the non-FEC portion of the OTU

The greatest number of overhead fields is found in the ODU, as Figure 6 illustrates, where a notable feature is the tandem connection monitoring (TCM) fields. The TCM active (ACT) field is reserved for future use to activate/deactivate TCM channels. Six TCMi (TCM1-6) fields are defined for use by network operators for management functions and contain elements similar to the SM, including a TTI, BIP-8, and alarm capabilities, discussed in the next section. The termination points of each TCMi can be defined within an operator's network, across a large public network at the user network interface points, or at protection switching points.

Path monitoring (PM) is a structure analogous to the SM and TCMi, except that it provides connection end-to-end monitoring and contains a TTI, BIP-8, and alarm capabilities. The automatic protection switching (APS) and protection communication channel (PCC) currently supports linear switching, as opposed to ring. Recommendations on the APS protocol are found in G.873.1.¹¹ APS is supported on different monitoring levels, more specifically: on the ODU path, on any of the TCMi, or based on SNC/I, which is a sub-network connection with inherent monitoring typically used to protect a path segment. The applicable APS level is derived from the actual value of the three least significant bits of the MFAS.

The experimental overhead (EXP) is not standardized and can be used freely by vendors and network operators while the GCC1 and GCC2 are very similar to the GCC0 except that they apply to the ODU. The fault type and fault location reporting communication channel (FTFL) is a 256 byte multiframe structure used to monitor path-level faults. The structure is divided into forward and backward directions that can indicate either no fault (value of 0), signal fail (value of 1), or signal degrade (value of 2), accompanied with an operator identifier. The signal fail indication is used to trigger alarms as described in the next section. The signal degrade information can be used in the protection switching process.

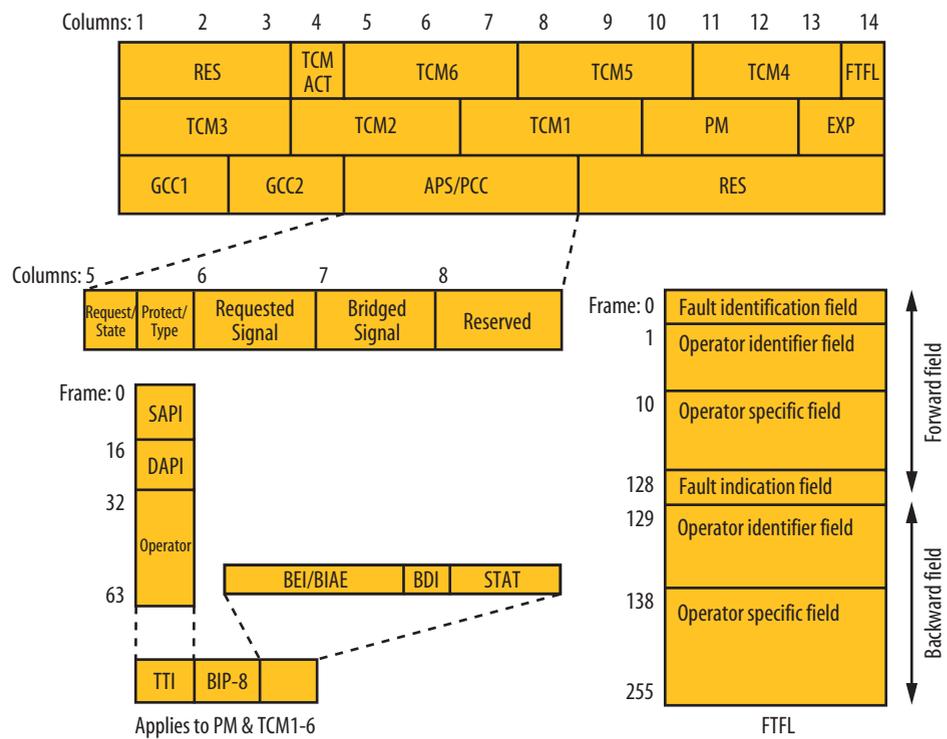


Figure 6 Overhead fields found in the ODU, showing the prominence of TCM fields

Figure 7 illustrates the OPU overhead. The Justification Control (JC) bytes provide for payload movements inside the OTN frame, which can occur when line and client clock sources are asynchronous. G.709 also supports synchronous clocking, where the payload is fixed relative to the overhead. There are three JC bytes where majority voting, meaning two out of three, is sufficient to carry out justification events. Positive justification events cause one of the payload bytes, identified as the position justification opportunity (PJO), to not contain payload information as the event occurs. Conversely, during a negative justification event, the negative justification opportunity (NJO) byte will temporarily carry part of the payload information.

The payload structure identifier (PSI) is a 256-byte multi-frame structure that contains the payload type (PT), which identifies the payload content such as asynchronous SONET/SDH, ATM, or GFP. G.709 supports the virtual concatenation function, which groups multiple OPU interfaces into a single OPU that runs at a higher rate. One advantage of virtual concatenation is that the channels within a group can travel on different physical paths through a network, before being joined back together, and can carry an overall payload corresponding to a higher transmission rate. In this case, the PT is set to a value of 06, and the virtual concatenation payload type (vcPT) indicates the actual payload type. The PT byte also specifies that an ODU multiplex structure, discussed earlier, is carried in the payload, which enables the multiplexing of multiple tributaries into a higher rate structure.

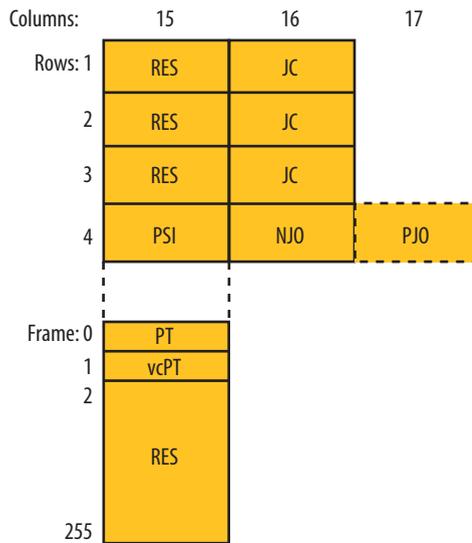


Figure 7 The OPU overhead

Faults and Alarms

The main fault indicators relating to the framing bytes—out-of-frame (OOF), loss-of-frame (LOF), out-of-multiframe (OOM), and loss-of-multiframe (LMF)—are detected using the overhead bytes; additional information can be obtained from G.798.¹²

The protocol enters the OOF state if it fails to find an FAS sub-pattern (FAS bytes 3, 4, and 5) for five consecutive frames. Similarly, OOM is declared when the received MFAS is out of sequence for five consecutive frames. LOF and LOM are the resulting indicators when the OOF or OOM states have been constantly observed for 3 ms, respectively.

Several indicators derive from the OTU SM and ODU PM and TCMi structures. For example, trace identifier mismatch (TIM) is raised when the received SAPI and/or DAPI values found in the TTI do not match the expected, pre-provisioned values. The detection of a frame slip, which can occur at the OTU or ODU TCM, generates an incoming alignment error (IAE) in the downstream direction. For OTU, the IAE bit resides in the SM while for the ODU TCMi; the 3-bit value of 010 in the Status (STAT) field indicates IAE. A corresponding backward incoming alignment error (BIAE) is inserted in the upstream direction by specifying bits 1011 in the backward error indication BEI/BIAE SM or TCMi fields. Concerning the STAT field applicable to the ODU TCMi, the loss-of-tandem connection (LTC) condition is declared when the tandem connection is in use and the received value in the TCMi STAT field is 000. The STAT value for an active TCM without an IAE condition is 001.

The ODU SM, ODU PM, and ODU TCMi all contain a BIP-8 and a BEI field. The BIP-8 values are byte-oriented parity checks that cover the OPU and client payload of the G.709 frame. The parity values are computed before the FEC is applied in the transmit direction and after the FEC is applied in the receive direction. The BIP-8 values are inserted in the BIP-8 field of the second frame following calculation. The maximum BER detection capability for each BIP-8 is 8 bits per 15,240 bytes corresponding to a rate of 6.56×10^{-5} . In the upstream direction, the BEI field is used for the back reporting of the number of BIP-8 errored blocks. A block is equivalent to a frame.

Three maintenance signals are available at the ODU, they are the alarm indication signal (AIS), locked defect (LCK), and Open Connection Indication (OCI). The LCK maintenance signal is generated on operator request to perform out-of-service tests that sends a repeating 01010101 pattern that fills the ODU, OPU, and payload. An open connection generates the OCI maintenance signal, which sends a repeating 01100110 pattern that also fills the ODU, OPU, and payload. The AIS is an all ones pattern that fills the ODU except for the FTFL, OPU, and payload that is a forwarded signal in the downstream direction sent as a response to a signal fail indication, such as in the FTFL or an incoming ODU-AIS. In the upstream direction, the response to continuity, connectivity, and maintenance signals, such as AIS, is a backward defect indication (BDI) signal indicated by a bit found in the PM, TCMi, or SM for the OTU. BDI triggers an alarm after it is received for five consecutive frames. The BDI and AIS also exist at the OTU layer, where the AIS is a 2047-bit polynomial sequence, called PN-11, that covers the full OTU frame including the framing bytes. In a practical example, the OTUAIS would be sent as a response to a loss of signal.¹³

At the OPU level, a payload mismatch (PLM) is declared when the received PT differs from the expected, pre-provisioned PT value.

Summary

G.709 initiated standardized internetworking within an OTN framework. The initial thrust focuses on SONET/SDH payloads to exploit FEC capabilities. The G.709 recommendation is proactive in that it enables development in the areas of tributary mapping, virtual concatenation, and supporting data protocols such as GFP. G.709 addresses the fundamental issues of bandwidth scalability and enabling high transmission rates, up to 40 Gbps, in addition to providing high signal integrity in long-haul networks.

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