The Operator's View of OTN Evolution

Martin Carroll, Verizon
Josef Roese, DT
Takuya Ohara, NTT

ABSTRACT

This article presents OTN evolution from an operator's point of view, including the history of the transport network, the role of the OTN, and the motivations and requirements for OTN evolution. First, a history of transport networks and the role of the OTN in today's networks is reviewed. Next, the motivation for the OTN evolution, operator requirements, and new OTN capabilities are described. Lastly, the future of the OTN is discussed.

INTRODUCTION

The International Telecommunication Union — Telecommunication Standardization Sector (ITU-T) Study Group 15 (SG15) is the primary standards development organization (SDO) responsible for Recommendations on optical transport network (OTN) and access network infrastructures. While the first Recommendations on OTN architecture were developed in the late 1990s, ITU-T SG15 recently reinitiated discussion on the OTN and how it will evolve to meet future network requirements. The primary trigger for this initiative was the IEEE standardization activities on higher-speed Ethernet, 40GbE and 100GbE. A new version of ITU-T Recommendation G.709, "Interfaces for the Optical Transport Network (OTN)," was approved in December 2009, providing many new capabilities, including support for higher-speed Ethernet transport.

OTN technology is indispensable for telecommunication operators to construct reliable and cost-effective high-capacity optical networks. It is expected that the OTN will continue to play a significant role in the evolution of operator networks supporting future high-bandwidth services and increased network efficiencies.

This article describes the motivation for network evolution to OTN technology from an operator's viewpoint. The next two sections provide a history of transport networks and the role of the OTN in today's networks, respectively. We then describe the motivation for OTN evolution, operator requirements, and new OTN capabilities that have been developed to support these enhancements. The final section discusses the future of OTN.

HISTORY OF TRANSPORT NETWORK TECHNOLOGIES

The transport network was first employed in operator networks to interconnect telegraph and telephone switches. In order to provide regional, nationwide, and international communications, the transport network had to support long distances covering several hundred kilometers to ever expanding networks reaching several thousand kilometers.

Figure 1 shows the evolution of transport network technologies and standards. In the early years analog copper and coaxial transmission systems were used for the transport network. Beginning in the 1970s, developments in digital technology and improvements such as time-division multiplexing (TDM) were introduced, resulting in digital copper and coaxial transmission systems supporting significantly greater bandwidth over longer distances. The analog/digital transmission systems required a large amount of amplification and regeneration processing equipment to overcome the high loss nature of copper and coaxial cable when extended over long distances.

The invention and maturity of semiconductor lasers and optical fibers opened the new era of optical fiber transmission in the 1980s. Optical fibers have much lower loss than copper or coaxial cable, providing operators with cost savings by reducing the facilities required for regeneration, amplification, and associated maintenance. Moreover, in the 1990s the introduction of optical amplifiers and wavelength-division multiplexing (WDM) technologies offered increased cost effectiveness and virtually unlimited capacity potential for the transport network.

Transport standardization in the early years consisted mainly of regional or country-specific specifications. The transport network multiplexing hierarchy used for digital copper and coaxial transmission systems, plesiochronous digital hierarchy (PDH), differed in North America, Europe, and Japan. This caused interoperability problems and increased costs as additional equipment was needed to interconnect networks using different multiplexing hierarchies. The equipment market was divided among regions, resulting in smaller market share and higher costs. Given this situation, the necessity of global standards for the transport network was recog-

 0163-6804/10/$25.00 © 2010 IEEE

nized as critical to support the growing global services market. International standards for the transport network would offer ease in interoperability and a reduction in network costs due to higher volume (off-the-shelf) production. By the end of the 1980s, the standard optical transport technologies, synchronous optical network (SONET) and synchronous digital hierarchy (SDH), were specified in the American National Standards Institute (ANSI) and ITU-T, respectively. SONET and SDH have highly reliable monitoring and management functionalities to support the operational needs of transport network operators. SONET and SDH optical fiber transmission systems became the predominant transport systems deployed in operator networks.

With network traffic increasing exponentially with the growth of Internet services, the maturity of WDM network technologies, and the emergence of newer high-bandwidth technology supporting more sophisticated client signals, the management of wavelength services had become a necessity. ITU-T SG15 initiated a study of optical transport networks in the 1990s to explore evolving network requirements and identify methods for improving and maximizing efficiency in optical transmission systems. This effort culminated between 2001 and 2003 with publication of a suite of OTN-related ITU-T Recommendations, including G.709.

THE ROLE OF OTN IN OPERATOR NETWORKS AND CURRENT DEPLOYMENT

The OTN technologies reside at the physical layer in the open systems interconnect (OSI) communications model. OTN is a layer 1 (L1) network technology supporting physical media interfaces. Operator networks are typically divided into three portions, as shown in Fig. 2: access network, metro network, and core network. OTN equipment is mainly used in the metro and core network in order to construct the regional and nationwide L1 network. OTN may also be utilized in the access network to provide bandwidth-intensive services for large customers, including business, Internet, education, and government customers. The OTN provides significant efficiency and flexibility for operators by accommodating various client signals at wavelength rates and sub-wavelength rates. Within the OTN, the optical channel data unit (ODU) provides efficient service packaging and overhead for operations and maintenance. ODU multiplexing is used to decouple the bit rate of services and the wavelengths used to support the services, allowing operators to optimize the WDM part of the OTN independent of the services. Current WDM technology permits wavelengths to be transported without reamplifying, reshaping, retiming (3R) regeneration over several hundred or thousand kilometers, further increasing the benefits to operators. One of the key enablers for long-distance high-speed WDM transmission is forward error correction (FEC). FEC bytes are appended at the trailing portion of the frame to gain additional system margin, as shown in Fig. 3. The transmitter appends FEC bytes, and a decoder at the receiver detects and corrects any bits that have become corrupted. OTN equipment, such as 10G and 40G WDM transmission systems, and reconfigurable optical add/drop multiplexing (ROADM) systems, are now widely deployed in operator networks around the world.

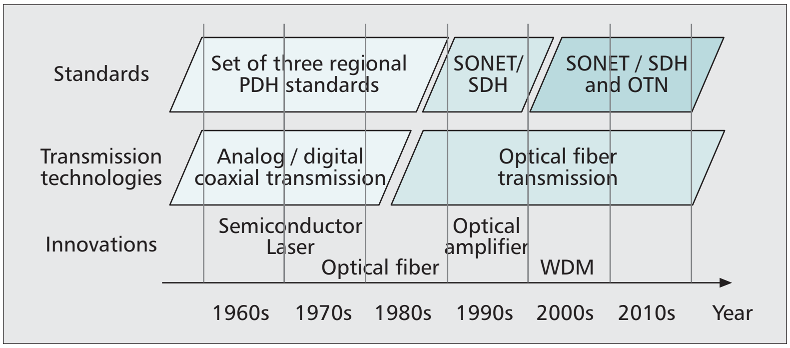

Figure 1. *Evolution of transport network technologies and standards.*

The role of OTN technology is to achieve reliable, cost-effective, versatile, and high-capacity optical networks. In order to realize these objectives, the OTN contains functionalities and mechanisms to support reliable and cost-effective transmission, accommodates multiple client signals, and provides operation, administration, and management (OAM) to meet the needs of both domestic and global network operators.

RELIABLE AND COST-EFFECTIVE TRANSMISSION

The OTN includes FEC functionality to increase transmission performance. ITU-T Recommendation G.709 specifies a standardized FEC code using Reed-Solomon (255, 239), which adds 6.7 percent overhead. Proprietary FEC codes can also be used for higher performance. The OTN equipment transmitter side adds the FEC coding, and the OTN equipment receiver side decodes the FEC code. As a result of the decoding, FEC improves the bit error rate (BER). For example, in the case of Reed-Solomon (255, 239) a BER of 10^{-4} before error correction can be improved to a BER of below 10^{-12}.

ACCOMMODATION OF MULTIPLE CLIENT SIGNALS

The OTN can accommodate various client signals; constant bit rate (CBR) clients and packet-/frame-based clients. For a CBR client, a particular client is mapped into an ODU by using either an asynchronous mapping procedure (AMP) or a bit-synchronous mapping procedure (BMP). Packet-/frame-based clients (e.g., Ethernet frames, IP and multiprotocol label switching [MPLS] packets) are mapped into ODUs by using the Frame-Mapped Generic Framing Procedure (GFP-F), which is specified in ITU-T Recommendation G.7041. ODUs may be mapped directly into an optical channel transport unit (OTU, i.e., wavelength) or multiplexed into an ODU of a higher bit rate. The different mappings provide maximum flexibility for efficient transport over OTN supporting a wide

OAM uses control plane and data plane technologies, which simplify operations for carriers, enable faster provisioning for customers, and provide the basis for broadband bandwidth-on-demand services as well as improved network reliability and availability.

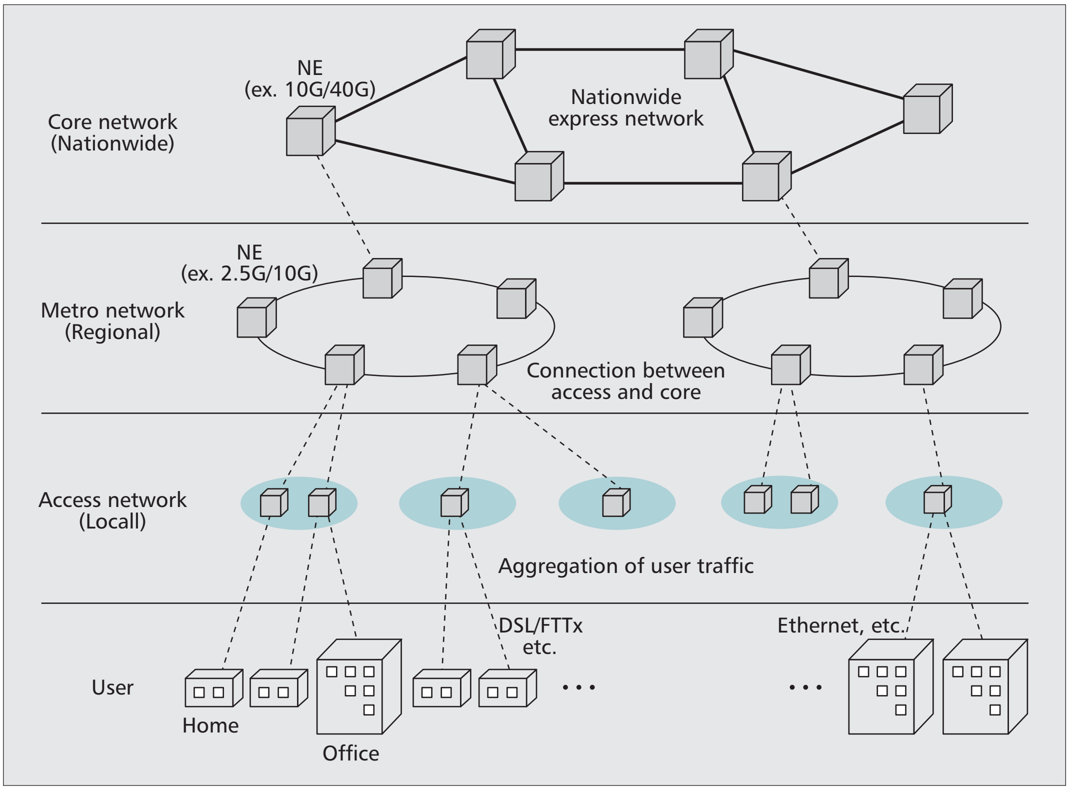

Figure 2. *Schematic figure of an operator's network: access, metro, and core. (NE: network element, DSL: digital subscriber line, FTTx: fiber to the X).*

range of both CBR clients and packet-/frame-based clients.

Control and Management (OAM)

A key feature of the OTN is the standardized OAM functionality for control and management of the transport network and services being carried. OTN specifies 0.4 percent of overhead bytes for OAM functionality including monitoring, alarm indication, protection switching, and dynamic provisioning. The OTN OAM functionalities are similar to those found in SONET and SDH but have been expanded to meet the needs of WDM technology. OAM uses control plane and data plane technologies, which simplify operations for carriers, enable faster provisioning for customers, and provide the basis for broadband bandwidth-on-demand services as well as improved network reliability and availability.

OTN Evolution

The OTN standards and technologies have evolved as industry trends and operator requirements dictated change. This section discusses the motivations and operator requirements, and a brief explanation of OTN evolution.

Motivations

Operators will continue to rely on the OTN to provide for future network services. The following are primary motivations influencing OTN evolution.

Traffic Change from Voice to Data Services — The type of traffic requiring transport is changing from voice to predominantly data. Today, there are many types of data traffic (e.g., email, texting, web browsing, video, IPTV).

Traffic Growth — With the growing use of Internet-based services coupled with the demand for bandwidth anytime and anywhere, network traffic is growing rapidly. Enhanced data services for businesses, diverse routing requirements, and distributed computing are among other examples impacting increased network traffic demand.

New On-Demand Variable Bandwidth Services — New types of services such as IPTV and video on demand have emerged. These services are not only high-bandwidth services; they also have variable bandwidth demand needs.

Evolution of Physical Connectivity from TDM to Ethernet (1/10GbE) — Transport service connectivity was traditionally based on TDM technology. IEEE 802.3 specifies standards for Ethernet interfaces that are rapidly becoming the predominant service type for homes, offices, and data centers. As the bit rates for Ethernet interfaces increased from 10 Mb/s to 1 Gb/s and 10 Gb/s, the preferred physical connection to the transport network has transitioned to Ethernet. Ethernet is one of the fastest growing CBR clients for the OTN.

Emergence of Higher-Speed Ethernet (40/100GbE) — After the standardization of 10GbE in 2002, increasing bandwidth demands and the need for higher-speed aggregation led the IEEE to initiate the standardization of higher-speed Ethernet. The new 40GbE and 100GbE standard was completed in June 2010. As routers begin to utilize these higher-speed Ethernet interfaces, the transport network will need to provide connectivity at these rates.

Diversity of New Types of CBR Client Signals — Although SONET and SDH interfaces are widespread, Ethernet signals have become one of the dominant CBR clients. Various other types of CBR client signals are also emerging, such as Fibre Chanel, serial digital interface (SDI), and common public radio interface (CPRI).

Requirements for OTN Evolution

As discussed above, the OTN will need to provide for future network services. Although each operator's specific requirements will differ because of the dependencies on their existing equipment, network size, future network vision, and so on, there are fundamental requirements for OTN evolution shared by many operators. This section highlights these common requirements.

Requirement 1: Support of Newly Emerging Client Signals — The first requirement is the support of newly emerging client signals. Although the original OTN bit rate and hierarchy were specified based on SONET and SDH in 2001, OTN was developed to also handle various other client signals. However, some CBR clients emerging after OTN standardization in 2001 could not be efficiently transported over OTN as their effective client signal rate did not correlate to the payload size of existing ODUs or ODU multiples. For example, GbE, 10GbE, and FC-1200 could not be efficiently handled by the 2001 version of ITU-T Recommendation G.709, as shown in Fig. 4. In addition, a new hierarchy level was needed to support 100GbE transport.

Other client signals have also emerged, as mentioned in the previous section. As customers request operators to provide transport services for these new client signals, operators require more OTN versatility to support these new clients.

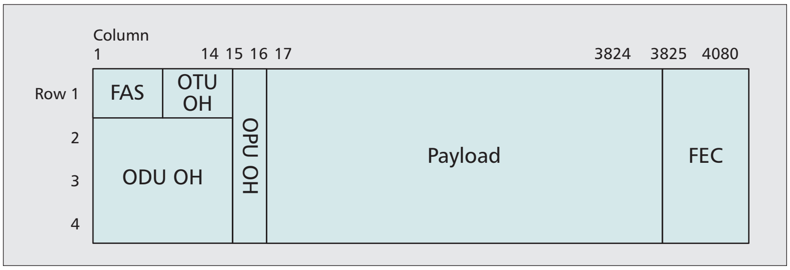

Figure 3. *Frame structure of OTN (FAS: frame alignment signal, OH: overhead).*

Requirement 2: Backward Compatibility — Equipment compliant with ITU-T Recommendation G.709 (2001) has been widely deployed in the operator's networks since the early 2000s. Operators require backward compatibility, seamless manageability, and interoperability between existing equipment and equipment supporting the newer OTN capabilities.

Requirement 3: Future-Proof Technology — As the costs for deploying and retiring equipment in the network are high, once equipment is implemented, it continues to be in service for many years. A service life of 10 years or more is common. Operators require not only a reliable technology that will function for many years, but also a future-proof technology that will not be quickly outdated and will support evolution.

Summary of New Technologies

In order to meet these requirements, the OTN was recently enhanced by specifying new ODUs/OTUs, a new size for tributary slots, new mappings for CBR clients, and a new generic mapping of lower-order (LO) ODUs into higher-order (HO) ODUs. This section briefly introduces some of the new capabilities specified in ITU-T Recommendation G.709 version 3,

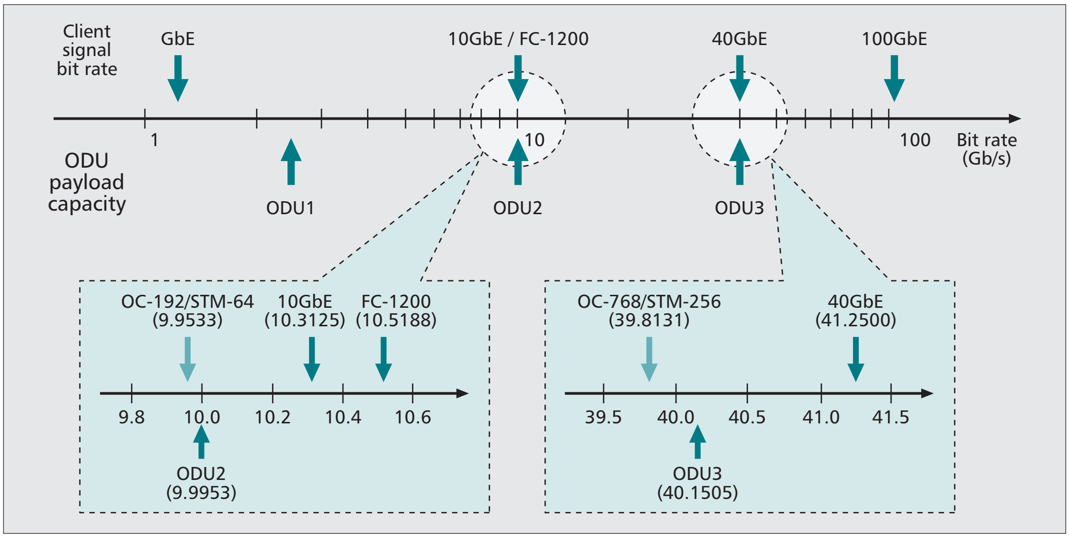

Figure 4. *Relationship between Ethernet bit rate and OTN payload capacity (2001 version of ITU-T Recommendation G.709).*

	Requirements	New capability
R1	**Support of newly emerging client signals**	
R1-1	GbE	Mapping into new ODU0 by using transcoding, GFP, and GMP
R1-2-1	10GbE	GFP-F mapping into extended OPU2 payload
R1-2-2	10GbE	Mapping into new ODU2e by using BMP
R1-3	40GbE	Mapping into ODU3 by using transcoding (1024B/1027B) and GMP
R1-4	100GbE	Mapping into new ODU4 by using GMP
R1-5	FC-1200	Mapping into new ODU2e by using transcoding (512B/513B) and BMP
R2	**Backward compatibility**	
R2-1	Support of already deployed equipment	Keeping existing specification
R2-2	Mixture of old and new equipment	Coexistence of 1.25 Gb/s and 2.5 Gb/s TS
R3	**Future-proof technology**	
R3-1	Support of any CBR and packet/frame client signals in the future	ODUflex (CBR): Mapping into new ODUflex by using BMP and then mapping into HO-ODU by using GMP ODUflex (packet): Mapping into new ODUflex by using GFP-F and then mapping into HO-ODU by using GMP
R3-2	ODU multiplexing	New 1.25 Gb/s TS size and a new generic mapping of LO-ODUs into arbitrary number of HO-ODUs TSs by using GMP
R3-3	Support of latency sensitive service	Delay measurement

Table 1. *Requirements and OTN evolution.*

approved in 2009. Table 1 compares the above requirements with the newly specified capabilities.

Enhancements for Requirement 1 — In order to meet requirement 1, support of newly emerging client signals, several new ODU/OTU structures and mapping procedures were specified in ITU-T Recommendation G.709.

For GbE transport, a new ODU0 was specified. GbE has a bit rate of 1.25 Gb/s. The earlier version of ITU-T Recommendation G.709 specified the minimum payload size as an ODU1 (approximately 2.5 Gb/s). As such, there was no suitable ODU to transport and monitor a single GbE. Therefore, in the recent update to ITU-T Recommendation G.709, ODU0 with a bit rate around 1.25 Gb/s was defined.

For transparent 10GbE LAN physical layer (PHY) transport, there was no defined support in the older ITU-T G.709. The bit rate of 10GbE LAN PHY (10.3125 Gb/s) is slightly larger than that of the ODU2 payload (9.9953 Gb/s). Of the multiple proprietary transport options, there were two leading options being used by operators to transport 10GbE LAN PHY. The first was a codeword-transparent 10GbE mapping using GFP framed into an extended ODU2 payload area; the second was a timing-transparent mapping of 10GbE into an ODU2e. The ODU2e, referred to as an over-clocked ODU2, could also be used to support FC-1200. ITU-T SG15 debated extensively which mapping to incorporate in the revised ITU-T Recommendation G.709 as 10GbE LAN PHY was growing in use. Some operators wanted to keep the existing ODU2/OTU2 bit rate because they did not have the need to support timing transparency for 10GbE or FC-1200, and they already had a widely deployed installed base using the standard ODU2 rate. Other operators wanted to add a new 10G bit rate ODU in order to provide timing transparent 10GbE LAN PHY. It was decided to add both mappings of 10GbE to the revised ITU-T Recommendation G.709. However, ODU2e multiplexing into HO-ODU3 and HO-ODU4 is the only recognized standard transport for this structure (the mapping of ODU2e into an OTU2e or HO-ODU3e is only specified in ITU-T G.Sup43).

For 40GbE transport, a new transcoding mechanism was specified. The bit rate of 40GbE (41.25 Gb/s) is greater than that of the ODU3 payload (40.15 Gb/s); therefore, a transcoding mechanism was required to accommodate 40GbE. Unlike the 10GbE case, a medium access control (MAC) rate of 40GbE (40.00 Gb/s) is lower than that of the ODU3 payload, so a transcoding technique was possible. Transcoding is the conversion of client signal coding, for example, from 64B/66B to 1024B/1027B in the case of 40GbE. (1024B/1027B is based on 512B/513B code. A 1027B code block comprises two 513B code blocks and one additional flag

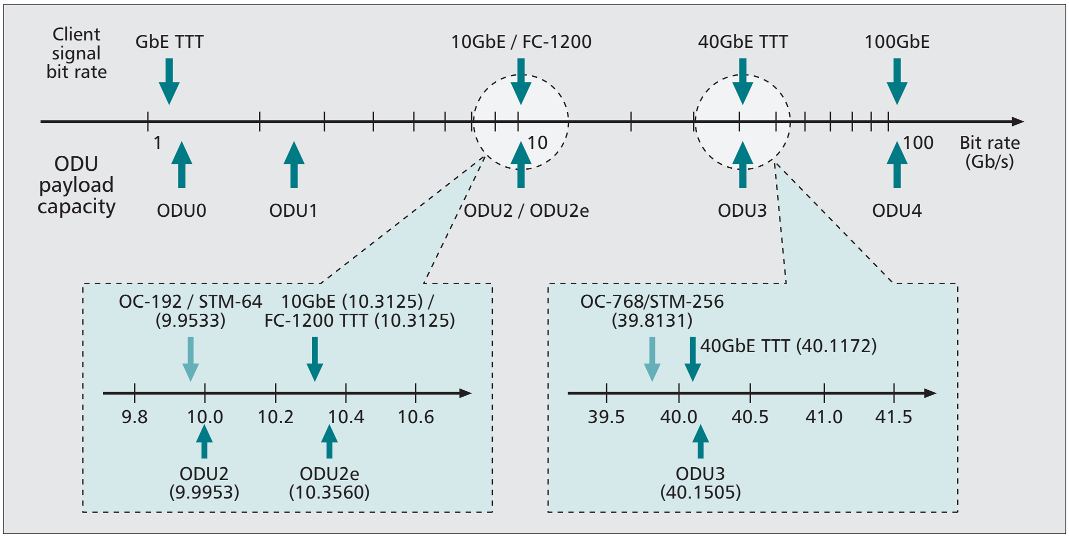

Figure 5. *Relationship between Ethernet bit rate and OTN payload capacity in the new version of ITU-T Recommendation G.709. (TTT: timing transparent transcoding.)*

A right-sized ODUflex could be used to interconnect these devices directly instead of using a non-optimal ODU structure or Ethernet rate. OTN equipment capable of switching the new ODUflex structure may then be used as transit switches.

parity bit to improve robustness.) By using transcoding, a client signal bit rate can be reduced from 41.25 Gb/s to 40.12 Gb/s; as a result, transcoded 40GbE can then be mapped into an ODU3. Transcoding provides transparency for the PCS code words (specified in IEEE 802.3 and 802.3ba).

For 100GbE transport, a new ODU4/OTU4 was specified. In the previous ITU-T G.709 version, ODU3 provided the highest bit rate. IEEE progress on the bit rate and structure of 100GbE allowed specification of the 100GbE mapping into a new ODU4 with an optimal bit rate at this time. The bit rate of the new ODU4 is slightly higher than needed for 100GbE, so it can also carry up to 10 × ODU2e signals.

Figure 5 summarizes the relationship between Ethernet bit rate and the OTN payload capacity in the new version of ITU-T Recommendation G.709.

Enhancement for Requirement 2 — In order to meet requirement 2, backward compatibility, no changes were made to the Recommendation that would impact networks and equipment built to the previous version of ITU-T Recommendation G.709. Newly defined ODU/OTUs have exactly same frame format as the previously defined frame format. All previously defined ODUs and newly defined ODUs can be multiplexed into the newly defined ODU4/OTU4. One of the primary differences between the previous OTN and the new OTN is the size of tributary slots (TSs). Originally, OTN had a TS size of 2.5 Gb/s. The new OTN has a TS size of 1.25 Gb/s due to the introduction of ODU0. The new version of ITU-T Recommendation G.709 allows the coexistence of both TS sizes in the network. Note, however, that an interface will support TS granularity of either 1.25 Gb/s or 2.5 Gb/s. A receiver can identify the TS rate of an interface by checking the payload type in the overhead. If an older receiver is misconnected, the older receiver will not recognize the 1.25 Gb/s TS granularity and will indicate the mismatch.

Enhancement for Requirement 3 — As mentioned above, there were many enhancements in order to support newly emerging client signals, mainly Ethernet. In the future other new client signals will need to be supported. It is desirable not to continue to add more structures (e.g., new ODUs) for supporting multiple different client signals, because the hierarchy and number of structures will continue to increase whenever new clients emerge, dramatically increasing complexity, cost, and interoperability issues. In order to provide a more flexible approach, the new version of ITU-T Recommendation G.709 specifies a generic future-proof ODU, ODUflex, and a new mapping procedure, Generic Mapping Procedure (GMP). ODUflex can have any fixed bit rate, and supports CBR clients and packet-/frame-based clients. ODUflex has two options: ODUflex (CBR) and ODUflex (packet). CBR clients are efficiently mapped into ODUflex (CBR) using BMP. ODUflex (packet) can accommodate a packet-based client signal via GFP-F. ODUflex are mapped into an integer number of TS of an HO-ODU by using GMP that distributes the data bytes and stuff bytes according to a sigma-delta algorithm over the assigned TS. For this reason, it is best to choose the bit rate of an ODUflex (packet) such that it utilizes 100 percent of the assigned TS. Unlike the classical fixed size ODUs such as ODU1, ODU2, and ODU3, ODUflex can provide a wide variety of payload sizes. ODUflex therefore offers high efficiency in client signal transport.

The use of LO-ODUflex and HO-ODU is described in the revised ITU-T Recommendation G.709. One possible application of ODUflex is the use of right-sized *channelized* OTN interfaces at Ethernet switches and IP/MPLS routers. A right-sized ODUflex could be used to interconnect these devices directly instead of using a non-optimal ODU structure or Ethernet rate. OTN equipment capable of switching the new ODUflex structure may then be used as transit switches.

It is expected that traffic demand will continue to increase due to the newer services such as IPTV and cloud computing. Therefore, as evolution to higher bit rate Ethernet signals occurs, their transport over OTN also will be required.

FUTURE OF OTN

This section discusses the potential for evolving the OTN in support of future networking needs.

SUPPORT OF NEW CLIENT SIGNALS (USING ODUFLEX/GMP)

ITU-T SG15 has completed a major revision of ITU-T Recommendation G.709 containing future-proof capabilities such as ODUflex and GMP, as mentioned in the previous section. When new CBR and packet-/frame-based client signals requiring transport over OTN emerge in the future, these client signals can be transported by ODUflex with a bit rate suitable for the client signal. If the bit rate of the new client signal is close to a conventional ODUk (k = 0, 1, 2, 2e, 3, 4), the client signal can be mapped directly into that ODUk using GMP.

OTU5 FOR HIGHER ETHERNET BIT RATES

The maximum payload capacity OTN can provide with one optical channel today is slightly higher than 100 Gb/s. This is suitable for transporting the current maximum Ethernet client, 100GbE. The next higher bit rate of OTU in the future, OTU5, will be dependent on the highest bit rate required by future client signals. The most promising higher-bit-rate client signal is the next high-speed Ethernet. It is expected that traffic demand will continue to increase due to newer services such as IPTV and cloud computing. Therefore, as evolution to higher-bit-rate Ethernet signals occurs, their transport over OTN will also be required.

In the standardization meetings and academic conferences, early discussion has begun regarding the next higher bit rate for Ethernet. Candidates include 400GbE, 1TbE, or possibly a higher rate. As mentioned earlier, OTN needs to be able to transport these client signals over long distances of up to several thousand kilometers. This will require overcoming transmission limitations such as transmission impairment mitigation and likely require significant advancement in device technologies. Innovations now being developed to support 100G transmission, such as advanced modulation formats (e.g., dual-polarization [DP]-quadrature phase shift keying [QPSK]), digital coherent receivers, and high-performance FEC, will help pave the way. Standardization activities for OTU5 are now being considered to keep in step with industry innovations. Cooperation between standardization bodies including the ITU-T, IEEE, OIF, and others is important for OTN to successfully meet the needs of the industry.

CONCLUSIONS

This article reviewed the OTN evolution from an operator's point of view. The background of OTN technology development, the role of OTN, and the motivations and requirements for OTN evolution are discussed. The recent major revision of ITU-T Recommendation G.709 offers not only greater optimization for Ethernet transport, but also sets the stage for the OTN to effectively support newly emerging client signals in the future. The OTN technology is positioned to provide cost-effective, reliable, future-proof high-capacity transport and will continue to grow as a critical transport technology in the operator networks, now and for the future.

ACKNOWLEDGMENT

The authors thank Deborah Brungard of AT&T for fruitful discussion.

BIBLIOGRAPHY

[1] ITU-T Rec. G.709/Y.1331, "Interfaces for the Optical Transport Network (OTN)," Dec. 2009.

BIOGRAPHIES

MARTIN CARROLL is a Distinguished Member of Technical Staff at Verizon, responsible for technical standards management and strategy for optical technologies supporting access and transport networks. He received a B.S. in civil engineering technology from Old Dominion University in 1981 and has 29 years of telecommunications and data communications experience with Verizon and its predecessor companies. He has worked across a wide range of technologies through various positions in outside plant engineering, product development, program management, technical regulatory and legal support, patent engineering, and standards management. Supporting key Verizon network and technology programs, he has participated in industry standards committees and fora for over 20 years, and is proactively contributing to initiatives at ITU-T SG 15, IEEE 802.3, FSAN, Ethernet Alliance, and ATIS.

JOSEF ROESE is a senior expert at Deutsche Telekom AG, Group Technology. He received his Dipl. Ing. at the University of Applied Science in Muenster, Germany, in 1981 and joined Deutsche Telekom in 1983. In the past 18 years he has worked for a number of organization units of Deutsche Telekom in the field of transport networks. The activities have covered evaluation of transport network technologies and network architectures. He participated in the standardization of SDH and since the end of 1990 in the standardization of OTN. As such, he contributed to Recommendation G.709 versions 1, 2, and 3. He is also engaged in IEEE 802.1.

TAKUYA OHARA [M] is a research engineer at Photonic Transport Network Laboratory, NTT Network Innovation Laboratories. He received his B.E. and M.E. degrees in electronic engineering from the University of Tokyo in 1998 and 2000, respectively. He joined NTT Network Innovation Laboratories in 2000. His research interests are optical fiber communication, in particular, high-speed and large-capacity optical transmission systems, and OTN evolution. He is involved in OTN standardization activities and has been active in ITU-T SG15 since 2006. He was a visiting researcher at AT&T Labs Research, Middletown, New Jersey, from 2007 to 2008, where he was involved in research on an optical path tracing technique.