50G-PON: The First ITU-T Higher-Speed PON System

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ABSTRACT

A suite of standards Recommendations has recently been developed in the ITU-T for a 50 Gb/s line rate passive optical network (PON) system. This 50G-PON system represents a significant leap in line rate from the 10 Gb/s systems being deployed today in fiber access applications. Achieving such a jump in performance necessitates an evolution in the underlying technologies. The 50G-PON system capitalizes on fundamental advances in the optical transceiver components working in conjunction with enhanced error correction and coding. It also introduces key innovations in activation procedures, contention-based operation, and expanded cryptographic features. With these improved capabilities, the 50G-PON system is ready to meet the new, and demanding, requirements of emerging services.

INTRODUCTION

During the last two decades, the passive optical network (PON) has been the key enabler of broadband optical access networks worldwide. As of December 2020, the number of fiber broadband subscribers reached 700 million globally, with the overwhelming majority served by PONs. The main motivation for each generational upgrade in PON technology has typically been the bandwidth demand increase.

In recent years, ultra-high-definition video, immersive video, cloud services for small/medium enterprises, as well as the fifth generation (5G) wireless transport have brought new opportunities for optical access network technologies, especially in supporting high, symmetric throughput, low latency, and high availability access services. In 2016 the International Telecommunication Union Telecommunication Standardization Sector (ITU-T) initiated a feasibility study of PON systems to meet these new requirements. Encouraged by the findings of the study, the ITU-T then initiated the Higher Speed Passive Optical Network (HS-PON) system project, supporting up to 50 Gb/s line rate per wavelength channel and targeting commercial deployment around 2025.

For the earlier generations of ITU-T PON systems, each ITU-T Recommendation series included its own documents addressing requirements, transmission convergence (TC), and physical media dependent (PMD) specifications. The HS-PON project, however, has a different vision. Laying the groundwork for future ITU-T PON systems, it is composed of two common documents applicable to multiple systems and extendable to multiple generations, along with a family of individual system-specific PMD Recommendations. In April 2021, the ITU-T reached a major milestone, consenting the first three Recommendations defining a 50G-PON system [1]:

- General Requirements (G.9804.1): The legacy features linked to deployed fiber infrastructure are complemented by support for new services requiring high capacity, efficiency, low latency, and security. Coexistence with, and migration from, the installed PON systems are essential.
- Common Transmission Convergence Layer (ComTC) specification (G.9804.2): This is defined in a line rate agnostic way and thus applicable to future single-wavelength time-division multiplexing (TDM) and multi-wavelength time-and-wavelength-division multiplexing (TWDM) PON systems.
- The single-wavelength 50G-PON PMD (G.9804.3) specification is the first in the HS-PON PMD family.

The other members of the family, the PMD Recommendations addressing higher line rates for TWDM and point-to-point wavelength-division multiplexing (PtP WDM) overlay systems, are in the ITU-T work plan.

In the remainder of this article, we first give an overview of the ITU-T PON technologies that preceded the development of the new HS-PON system project. Then we highlight the major innovations in the ComTC and 50G-PON PMD specifications. Finally, we discuss future extensions of the HS-PON standards prior to giving the concluding remarks.

OVERVIEW OF ITU-T PON SYSTEMS AND STANDARDS

PON, as a type of optical access network, refers to a point-to-multipoint fiber infrastructure, called the optical distribution network (ODN), with entirely passive branching points. The term *PON system*, on the other hand, denotes a set of active equipment designed to operate over an ODN using a particular suite of PMD layer, TC layer, and management layer protocol specifications. A PON system typically includes the following

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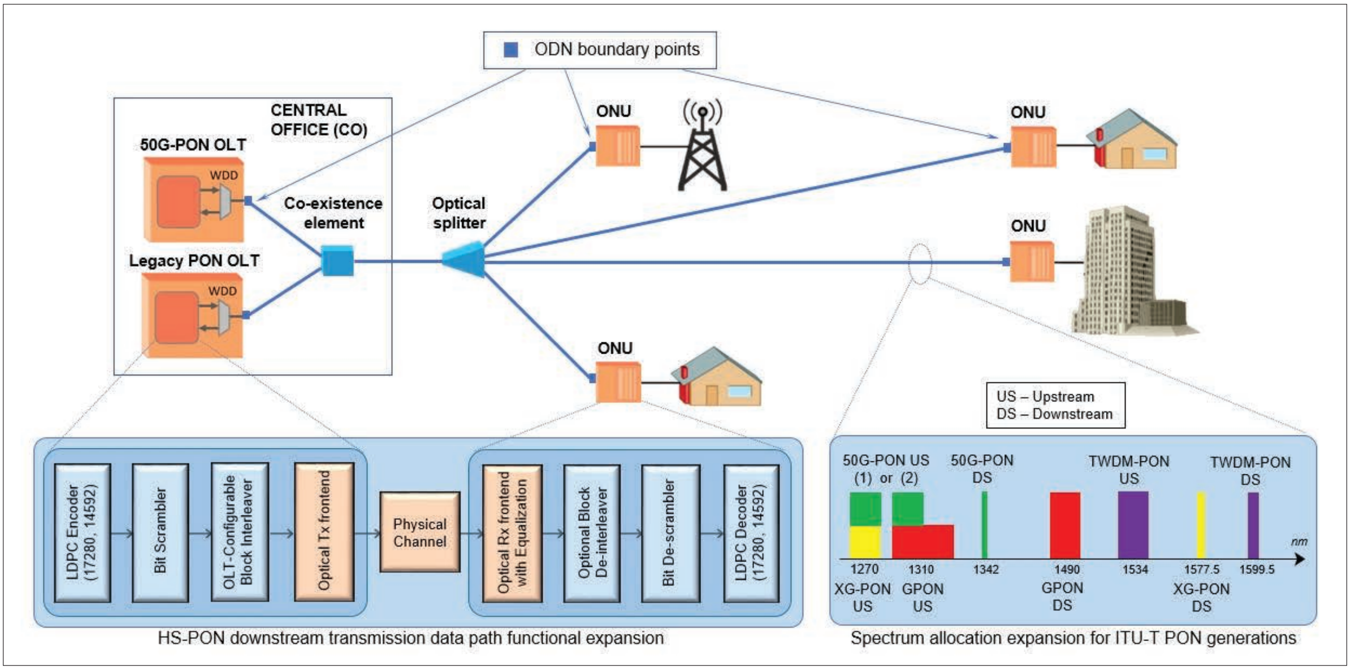

FIGURE 1. PON system architecture with deployment scenarios, downstream transmission data path, and PON spectrum allocation. Note: The ONU population may include both 50G-PON ONUs and legacy PON ONUs.

active equipment: the optical line terminal (OLT) placed at the root of the ODN in a central office (CO) location, and the optical network units (ONUs) connected to the leaves of the ODN and located at the customer sites. The ODN generally consists of optical fibers, connectors, optical power splitters, and wavelength multiplexers. Wavelength-division duplex (WDD) is employed for bidirectional transmission over a single fiber. A typical PON system is illustrated in Fig. 1, where peach and blue denote active and passive elements, respectively.

The ITU-T has developed specifications for several generations of PON systems. Notable characteristics of these systems are summarized in Table 1.

The first commercially successful system was broadband PON (B-PON), for which the initial standardization was completed in 1998 (G.983 series) [2]. Wide-scale B-PON deployment started in 2000, and it remains in service today. Following this, the gigabit-capable PON (G-PON) system was standardized in 2004 (G.984 series) [3]. The 2.5 Gb/s downstream and 1.25 Gb/s upstream G-PON variant became the most widely deployed PON system to date.

Higher line rates of 10 Gb/s were addressed by the XG(S)-PON system with an asymmetric line rate variant (G.987 series) [4] and a symmetric one (G.9807 series) [5]. These 10-Gbit systems have experienced rapid growth in deployment in recent years. Going beyond 10 Gb/s nominal line rate, the IEEE 802.3ca 50G Ethernet PON (EPON) Task Force recently defined a system based on 25 Gb/s nominal line rate, while the ITU-T has followed a path to an even higher nominal line rate of 50 Gb/s [6].

The ITU-T PON systems described so far in this section use a single wavelength channel per direction. Exploiting TWDM with four or eight 10 Gb/s wavelength channel pairs, the next generation PON system, or NG-PON2 (G.989 series) [7], added the wavelength dimension to the PON world. The NG-PON2 systems are today at the start of field deployment.

The deployed ITU-T PON systems belong to the TDM class: within a single wavelength channel pair, they employ TDM in the downstream direction and time-division multiple access (TDMA) in the upstream direction. The continuous-mode downstream transmission is partitioned into fixed size 125 μs frames, which also provide time reference points for the burst-mode upstream transmission. The main operating principle of TDM/TDMA PON systems is avoiding burst data collisions in the upstream by accurately measuring the round-trip time and establishing a per-ONU equalization delay to separate the ONU transmissions in time. Each ONU buffers user data while waiting for its upstream transmission allocation, identified by an allocation identifier (Alloc-ID) associated with that ONU. When its allocation arrives, the ONU sends its data in bursts toward the OLT. The Alloc-ID assignment and other low-latency operation and maintenance tasks are performed using the Physical Layer Operation, Administration and Maintenance (PLOAM) messaging channel.

An extensible, and continually expanding, standard for ONU management is specified in ITU-T Recommendation G.988 [9]. The ONU Management and Control Interface (OMCI) is reused for HS-PON to complete the suite of standards for 50G-PON.

50G-PON continues to use TDM/TDMA and currently supports a 50 Gb/s downstream line rate and two upstream line rate options (25 Gb/s and 12.5 Gb/s). It can operate over deployed ODNs while coexisting with PON systems already in service. This is made possible through a wavelength plan that facilitates WDM of different PON generations on the same ODN, as shown in the spectrum expansion of Fig. 1. Notably, the 50G-PON wavelength plan allows coexistence with

	Downstream rate (Gb/s)	Upstream rate (Gb/s)	Downstream wavelength (nm)	Upstream wavelength (nm)
B-PON	0.622	0.155	1480–1500	1260–1360
G-PON	2.488	1.244	1480–1500	1290–1330
XG(S)-PON	9.952	9.952 2.488	1575–1580	1260–1280
NG-PON2	4 × 9.952	4 × 9.952	1596–1603	1524–1544
50G-PON	49.7664	49.7664* 24.8832 12.4416	1340–1344	1260–1280 or 1290–1310

* Expected in future releases.

TABLE 1. ITU-T PON systems and standards.

GPON or XG(S)-PON to enable a smooth system upgrade path through the use of the appropriate upstream wavelength option, that is, spectral options (1) or (2) in Fig. 1.

At the network level, the spectral coexistence could also enable new services to be delivered as an overlay to legacy PON systems; for example, legacy fiber to the home (FTTH) overlaid with new wireless transport. The five-fold increase in per-wavelength downstream line rate from previous PON generations coupled with new TC features (elaborated in the following section) further support the necessary capacity expansion, low latency, higher efficiency, and improved security demanded at the service level.

The 50G-PON downstream data path is illustrated in the functional expansion of Fig. 1, where blue and pink blocks represent the physical interface (PHY) adaptation sublayer of the TC layer and the PHY itself, respectively. Those functional blocks that are subject to innovation in HS-PON are further discussed in the following two sections.

Main Advances and Innovations in ComTC

Capitalizing on the TC layer functional similarity within the previous PON systems [3–5, 8], the ComTC specification is designed to support not only 50G-PON but also future PON systems. It encompasses single-wavelength-channel operation as a special case of multiple-channel operation, and parameterizes the nominal line rate using a fundamental rate (e.g., 12.4416 Gb/s in the 50G-PON case) and a set of integer factors as multipliers.

Emerging requirements on high capacity, efficiency, flexibility, latency, bit error mitigation, and security drive innovations in the ComTC design. The major technical improvements incorporated into the ComTC specification include: an enhanced ONU activation procedure — to speed up the process and provide additional flexibility; contention-based operation — to increase the upstream bandwidth utilization; advanced coding and interleaving — to mitigate the anticipated bit error characteristics and improve receiver sensitivity; and expanded cryptographic capabilities — to strengthen user data security generally and support the regional differences in security requirements.

In the remainder of this section, these major technical improvements are described in further detail.

ONU Activation Enhancement

In the course of activation, the ONUs respond with their serial numbers to the upstream bandwidth allocations, which are identified by activation Alloc-IDs. If successful, an ONU is assigned a logical identifier, called ONU-ID, and from that point on receives directed bandwidth allocations. The activation Alloc-IDs, however, are necessarily contention-based. This means that the collisions between transmissions originated by different ONUs are possible and must be accounted for. The ONU activation enhancements in ComTC include dynamic assignment of activation Alloc-IDs, flexible specification of the upstream burst preamble, and an advanced collision resolution protocol.

Dynamic Assignment of Activation Alloc-IDs: The previous ITU-T PON systems [4, 5, 8] provided a set of well-known reserved Alloc-IDs intended to activate ONUs with specific pre-defined upstream line rates. ComTC allows additional dynamic assignment of activation Alloc-IDs, providing additional flexibility to the ONU activation process. A dynamically assigned activation Alloc-ID can be associated with a specific upstream line rate or a specific combination of upstream line rates as required by the network operator, or with a set of non-rate parameters, such as maximum random delay and retransmission probability.

Flexibility of the Upstream Burst Preamble: Each transmission burst starts with a preamble followed by a delimiter that allows the OLT receiver to correctly detect and delineate the burst. The guard time, preamble, and delimiter form the overhead associated with each transmitted burst. During ONU activation, the OLT does not know in advance which ONU will respond to a serial number allocation. Nevertheless, for the successful acquisition of an upstream burst signal from an arbitrary ONU, several OLT receiver functions, such as amplitude recovery, clock recovery, and equalizer adjustment, need to converge. To improve convergence, a flexible multi-segment preamble is introduced, where each segment is optimized for one of the aforementioned receiver functions. ComTC enables the OLT to define preambles with up to four segments, each with a different data pattern: either a periodic set of customizable bits or a standardized pseudo-random binary sequence.

Set-Splitting Collision Resolution Protocol: When the OLT detects a collision between transmissions originated by multiple ONUs in a time interval associated with an activation allocation, a collision resolution period ensues. In previous ITU-T PON systems, the method of collision mitigation at the activation stage was persistent retransmission with delay randomization. This method does not guarantee that the collision resolution period is free of subsequent collisions, but it does prevent persistent collisions between the same ONUs. When longer preambles are used, this approach loses its efficiency due to higher probability of subsequent collisions. To solve this issue, ComTC uses an advanced collision resolution protocol based on set-splitting, which is reminiscent of the Capetanakis-Tsybakov-Mikhailov (CTM) multiple access protocol [10].

The ComTC adaptation of the CTM protocol extends the PLOAM messaging to provide the

ONUs with exhaustive feedback on the outcome of the activation as observed by the OLT: namely, successful transmission, collision, idle, and more complex outcomes if two or more events have been detected. The set of ONUs involved in a recent collision is stochastically split into two subsets: the ONUs in the first subset remain eligible to retransmit on the next allocation, whereas the ONUs in the second subset delay their activation attempts until all ONUs in the first subset are successfully activated. Each ONU controls its retransmission eligibility based on the OLT feedback.

THE CONTENTION-BASED OPERATION

In TDM/TDMA PON systems, once the ONUs are activated, the transmission bursts from different ONUs follow each other, spaced by a guard time. Normally, at any given instant, only a few ONUs have data to send; however, to identify active ONUs, the OLT has to allocate a burst to each ONU. Providing such directed allocations for ONUs with no upstream traffic in a typical case may result in a waste of 15–25 percent of upstream bandwidth.

To improve bandwidth utilization, the ComTC specification introduces contention-based operation. A new class of explicitly assignable broadcast Alloc-IDs is introduced. Rather than being associated with a particular ONU, such Alloc-IDs are associated with a specific contention-based function, such as inactivity support, wavelength protection in TWDM PON, and watchful sleep. Once the OLT assigns a broadcast Alloc-ID for a contention-based function, it may withdraw directed allocations to the ONUs. If the OLT detects a collision in a time interval associated with a broadcast allocation, it temporarily restores the directed allocations to identify those that do require upstream transmission bandwidth to satisfy their needs. As illustrated in Fig. 2, contention-based operation employs one broadcast allocation to replace multiple directed allocations. The upstream bandwidth utilization is thus improved by avoiding non-productive use by idle ONUs.

ADVANCED CODING AND INTERLEAVING

The higher the line rate, the more challenging it is to balance the optical link budget. To improve receiver sensitivity, low-density parity-check (LDPC) codes for forward error correction (FEC) are used instead of the conventional Reed-Solomon (RS) codes. For 50G-PON, an LDPC(17280,14592) code with a code rate of 0.844 is selected for the downstream direction and as a base code for the upstream direction. In the downstream direction, one innovation is the inclusion of the downstream physical synchronization block in the first LDPC code word for better protection against high input bit error ratio (BER). Another innovation is the appropriate code word puncturing scheme selected to enable both high coding gain and an integer number of code words per 125 μs downstream frame. The receiver may apply either hard-decision or soft-decision LDPC decoding, leading to gross coding gains of about 2.6 dB and 3.9 dB, respectively, over the conventional RS(248, 216) code. In the upstream direction, the OLT may also select shorter LDPC codes for the individual ONUs, targeting either higher throughput or higher loss budget. To reduce complexity, all LDPC codes are derived by shortening and puncturing of the same parity-check matrix.

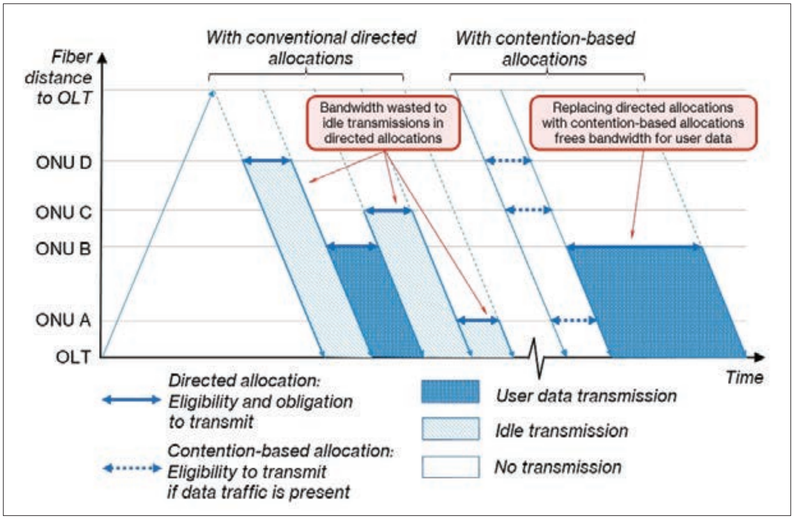

FIGURE 2. Contention-based operation.

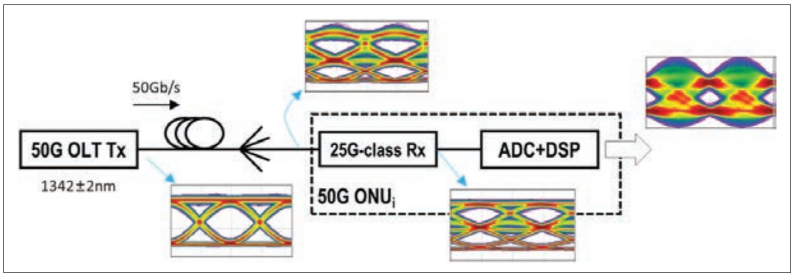

FIGURE 3. Exemplary 50G-PON downstream transmission link with cost-effective 25 Gb/s-class receiver. Insets: qualitative eye diagrams at key points.

The expected use of digital signal processing (DSP) techniques for equalization and chromatic dispersion compensation may result in error clustering, which would degrade the LDPC performance. This is effectively mitigated in the downstream by interleaving the bits across each group of four consecutive LDPC code words [11, 12]. The OLT may disable downstream interleaving to reduce downstream latency. The ONU receiver determines the presence of interleaving autonomously during the synchronization stage. No interleaving is applied in the upstream because of the variable burst duration and hence variable number of code words per upstream burst.

SECURITY IMPROVEMENTS

50G-PON inherits the threat model and basic security mechanisms of previous PON systems. To strengthen HS-PON against potential threats considering present and anticipated improvements in cryptanalytic capabilities and to allow the use of HS-PON in critical infrastructure applications, such as power grid and manufacturing, the need arises to expand its cryptographic features. The specific security capabilities are enhanced by adding the mandatory support of the advanced encryption standard (AES) with a 256-bit key [13] and additional optional support of ISO-approved regional ciphers. The enhancements satisfy different data security requirements in various regions. They also facilitate HS-PON applications in new markets such as smart power grids. Enhanced security features are configured by the OLT upon completion of ONU activation.

As the 50GPON system is the first to consider using DSP-based equalization and strongly bandwidth-limited reception, this drives the need for new metrics for specifying the transceivers in order to ensure physical layer interoperability.

Main Advances and Innovations in 50G-PON Transmission

Increasing the data rate in ITU-T PON systems from the 10 Gb/s of the current generation is enabled by significant innovations in the optical transceiver technologies in conjunction with complementary advances in the high-speed electronics and anticipated use of DSP.

Considering the downstream link in 50G-PON, which starts at the OLT and terminates at the ONU, this requires innovative approaches to enable a practical system. Network operators require 50G-PON to operate over deployed ODNs with high optical budgets due to the use of optical power splitters; for example, the C+ class optical path loss is 32 dB. By the nature of the PON architecture, the OLT transmitter is shared by all users, and the ONU receiver is provisioned on a per-user basis. Thus, the overall system cost is generally minimized by keeping the ONU optical components low-cost and putting any increase in cost and complexity on the OLT side.

To enable high receiver (Rx) sensitivity, a non-return-to-zero (NRZ) modulation format is adopted for 50G-PON (the same as used for previous PON systems). At the OLT, a compact optically amplified transmitter (Tx) can be used. Such a transmitter may be implemented as monolithically integrated electro-absorption modulated laser (EML) and semiconductor optical amplifier (SOA). Such an EML+SOA Tx can deliver over 10 dBm into the fiber at the OLT while being modulated at 50 Gb/s [14]. Accumulated fiber chromatic dispersion (CD) up to 77.1 ps/nm (at 1342 ± 2 nm) must be tolerated in the downstream link. In order to limit the penalty due to CD-induced inter-symbol interference (ISI), the wavelength chirp of the EML+SOA Tx should be minimized. A chirp factor (α) of less than 0.5 is possible using EML+SOA Tx devices [13].

At the ONU, the assumption is that a nominal 25 Gb/s-class Rx will be used. This is driven by the availability of suitable avalanche photo-diode (APD) devices and the objective to keep the ONU cost low. Currently, 25 Gb/s-class APD devices (25G-APDs) are mature, commercially available components, but 50 Gb/s-class APD devices are still just emerging from research labs. Furthermore, the 25G-APDs generally offer better performance concerning key parameters such as the avalanche gain and responsivity. It has been verified in the course of ITU-T study that a cost-effective 25G-APD Rx followed by equalization can offer high sensitivity at 50 Gb/s. The necessary equalization can be implemented using DSP in integrated circuits that benefit from cost/size/speed scaling thanks to Moore's Law. The DSP effectively compensates for both the limited bandwidth of the Rx and the CD-induced ISI.

The key elements in the full downstream link are illustrated in Fig. 3. At the ONU side, an analog-to-digital converter (ADC) is used to convert the received waveform into digital samples. For the purpose of developing the 50G-PON standard, this function was assumed to be implemented at 1 sample/symbol with 5-bit resolution. Following this, equalizers such as feed-forward equalizer (FFE), decision feedback equalizer (DFE), maximum likelihood sequence estimation (MLSE), and Bahl–Cocke–Jelinek–Raviv (BCJR) decoding may be used to recover the original bit sequence. The output signal from the PMD layer is specified with a reference BER of 10^{-2}, which will allow an output BER of below 10^{-12} after FEC decoding in the TC layer. Hereby, a careful co-design of the PMD and TC layers is beneficial. For example, the correlated errors caused by digital equalization in certain link scenarios may degrade the FEC decoding performance, but this degradation is mitigated by bit interleaving (as discussed above). Soft decision input to the ComTC layer, on the other hand, can improve FEC decoding performance.

With the increase of line rate, requirements on jitter generation and jitter tolerance, which are associated with clock recovery, become more critical. 50G-PON departs from previous PON generations [3–5, 8], where the filter frequencies of clock recovery and jitter tolerance were scaled with the symbol rate. In 50G-PON, the characteristic frequencies for the jitter tolerance specification remain the same as those in XG(S)-PON, which keeps the transition frequency (f_T) at 4 MHz. The tolerated jitter amplitudes scale with the unit interval (UI), and remain at 0.75 UI for frequencies below 400 kHz and at 0.075 UI for frequencies above 4 MHz.

As the 50G-PON system is the first to consider using DSP-based equalization and strongly bandwidth-limited reception, this drives the need for new metrics for specifying the transceivers in order to ensure physical layer interoperability. The Tx quality must meet a minimum level, and the equalization capability of the Rx must be powerful enough. To achieve this, 50G-PON adopts an extended version of the Transmitter Dispersion and Eye Closure (TDEC) metric used in Ethernet transceivers as defined by the IEEE [15]. This TDEC metric is extended in 50G-PON by defining a reference equalizer based on 13-tap symbol-spaced FFE before evaluating the TDEC. Furthermore, a 4th order Bessel-Thomson reference filter with 18.75 GHz bandwidth is also included to represent the typical frequency response of a 25G-APD Rx.

The TDEC of an OLT Tx is measured by using the worst case fiber link by analyzing histograms from the received eye diagram in an oscilloscope or a similar instrument. This gives an accurate measure of the Tx quality and transmission performance. TDEC values from 2.0 dB to 5.0 dB are permitted in 50G-PON. An OLT Tx with a higher TDEC value must transmit at a higher optical modulation amplitude (OMA) in order to be standard-compliant. In a similar manner, the ONU Rx must meet a certain sensitivity when measured using a signal with a TDEC value within the defined range. Figure 4 shows how the Tx OMA and the Rx sensitivity in OMA vary with TDEC to ensure a link budget of 29/32 dB is always met such that physical layer interoperability is reliably achieved.

Note that in previous ITU-T PON standards, the PMD parameters are defined in a more rigid way. For example, all Tx must satisfy all the PMD parameters and reserve a fixed optical path penalty by considering the worst case. On the other hand, 50G-PON allows a range of TDEC values, as illustrated in Fig. 4, for various Tx parameter trade-offs while still achieving a given link budget. Example parameters that impact TDEC, and hence may be traded off by a Tx, are extinction ratio, optical signal-to-noise ratio, chirp, and rise/fall time. Such flexibility in the specification supports more options for optical Tx technologies without sacrificing interoperability, thereby enabling a diverse and competitive supply chain for 50G-PON.

FUTURE EXTENSIONS

In the G.9804 series amendment phase, further extensions to the PMD and ComTC specifications are expected. The first version of G.9804.3 specifies the PMD layer for downstream transmission at 50 Gb/s and upstream transmission at 25 Gb/s and 12.5 Gb/s, for a maximum fiber distance of 20 km. The specifications for upstream transmission at 50 Gb/s and maximum fiber distance of 40 km are anticipated.

Upstream transmission at 50 Gb/s requires additional performance improvement techniques to support the same power budget classes as at lower line rates. Several promising approaches are discussed:

- Increased optical output power of the ONU transmitter, for example, realized by integration of an SOA booster amplifier
- Use of equalization means, for example, techniques discussed in the previous section for the downstream direction, but modified to be burst-mode-compatible
- Improving OLT receiver sensitivity, for example, using lower-noise SiGe APD technology or an SOA-based pre-amplifier receiver
- Application of soft decision LDPC decoding at the OLT with optimized LDPC code word size

To extend the ODN length to 40 km, the major challenge of large chromatic dispersion at the downstream signal wavelength of 1342±2 nm needs to be overcome. Possible paths forward include:

- Reducing OLT transmitter chirp parameter to well below 0.5, for example, using new OLT transmitter designs
- Application of enhanced equalization techniques, such as MLSE or BCJR, to compensate for dispersion- induced signal and inter-symbol interference
- Use of soft decision LDPC decoding

Future ComTC extensions for G.9804.2 are multifold. First, the requirement to support network slicing is under active study. The study results may introduce new content to G.9804.2 clarifying resource allocation and quality of service (QoS) provisioning in 50G-PON. Second, further investigation of the upstream FEC is to be conducted as the default upstream FEC code of 50 Gb/s, and optional upstream FEC codes of 12.5 Gb/s and 25 Gb/s, remain to be specified. Flexible LDPC code selection could provide a powerful tool to counteract equalizer-induced or other types of impairments. Other items for further study include:

- Accurate time offset carrying over 50G-PON for mobile applications
- Multi-channel activation for channel bonding
- Security enhancement addressing emerging threats

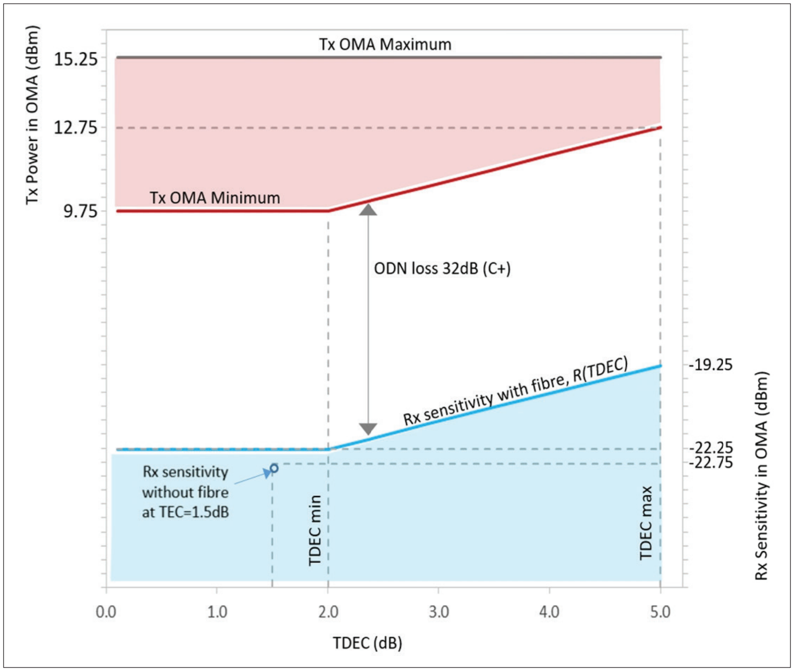

FIGURE 4. OLT transmitter OMA and ONU receiver sensitivity (in OMA) vs. TDEC of the OLT transmitter.

CONCLUDING REMARKS

The HS-PON project expands the capabilities of ITU-T PON beyond those of previous generations by increasing the line rate as well as enhancing its robustness and efficiency, while crucially supporting coexistence with installed deployments. As the first project output, the 50G-PON marks the beginning of a new generation of ITU-T Higher Speed PON systems.

Innovations in optical transceiver technology, combined with advanced FEC coding and interleaving schemes as well as the unique transmission convergence layer modifications aimed at efficiency improvements and flexibility enhancements, result in a cost-efficient PON system. The 50G-PON systems support accelerated growth in user data traffic combined with increased 5G wireless transport capacity demand and enable new applications such as the tactile Internet, smart power grids, industrial manufacturing, and autonomous vehicles.

The COVID-19 pandemic has resulted in an increased focus on access networks due to a major shift in the priority use cases. For example, videoconferencing, remote healthcare, and remote education have become essential necessities in most households. As a result, new bandwidth usage profiles greatly exceed the previous projections and accelerate the need for reliable higher-speed optical access networks. The 50G-PON system will undoubtedly be the key to meeting these future network demands.

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We are determined to preserve the memory of Tim Williams († 2020) and Kent McCammon († 2020) not only as contributors to the project and members of its original editorial team, but also as long-time caring mentors, supportive colleagues, and good friends for many.

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