Coherent PON Poised to Become Cable's Next Long Term Evolution Access Platform

A Technical Paper prepared for SCTE by

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1. Introduction and Motivation

A passive optical network (PON) that has the benefits of point-to-multipoint passive topology for highly efficient fiber utilization has become the dominant optical access architecture for the operators in the current fiber to the premise (FTTP) deployments. The global PON equipment market is forecast to grow at a compound annual growth rate (CAGR) of 12.3% from 2020 to 2027, approaching $16bn in 2027, from $7bn in 2020. FTTP infrastructure builds are gaining momentum in most countries, with the global fiber access household penetration forecast exceeding 47% by 2026 [1], representing more than 1.1 billion subscriptions. Furthermore, 10G FTTP (and higher) is offered to residential subscribers by more than 55 communications service providers (CSPs). Ever-increasing bandwidth demand is the key driver for fiber access, along with demand for low-latency, reduced jitter, and improved quality of experience (QoE) by VR-based games and cloud applications [1].

In a typical PON system, an optical line terminal (OLT) at Hub or central office (CO) performs bidirectional communication with multiple optical network units (ONUs) at customer premises over a passive optical distribution network (ODN). A time-division-multiplexed PON (TDM PON) based on power-split ODN (PS-ODN) represents the most common PON architectures deployed so far. For a TDM PON, the OLT broadcasts the downstream (DS) signal to each ONU in continuous mode on a single wavelength channel. In the case of upstream (US) transmission, each ONU is assigned for a specific timeslot to transmit a burst of upstream data on another wavelength channel. The other type of PON architecture is wavelength-division-multiplexed (WDM) PON. WDM PON assigns dedicated wavelength for each ONU to realize virtual point-to-point optical connection. The corresponding ODN is wavelength-routed ODN (WR-ODN), which has an intrinsic wavelength routing capability through wavelength splitters. Time and wavelength division multiplexed (TWDM PON), in comparison, is the third type of multiplexing technique that combines TDM and WDM. Accordingly, the ODN is wavelength-selected ODN (WS-ODN), which relies on tunable optical filters to provide a wavelength selection capability in the ONUs. Among these different PON architectures, TDM PON offers much higher aggregated bandwidth for efficiently handling bursty traffic and with cost and complexity advantage, becoming the most popular optical access network. Unless otherwise stated, TDM PON is the focus of this paper.

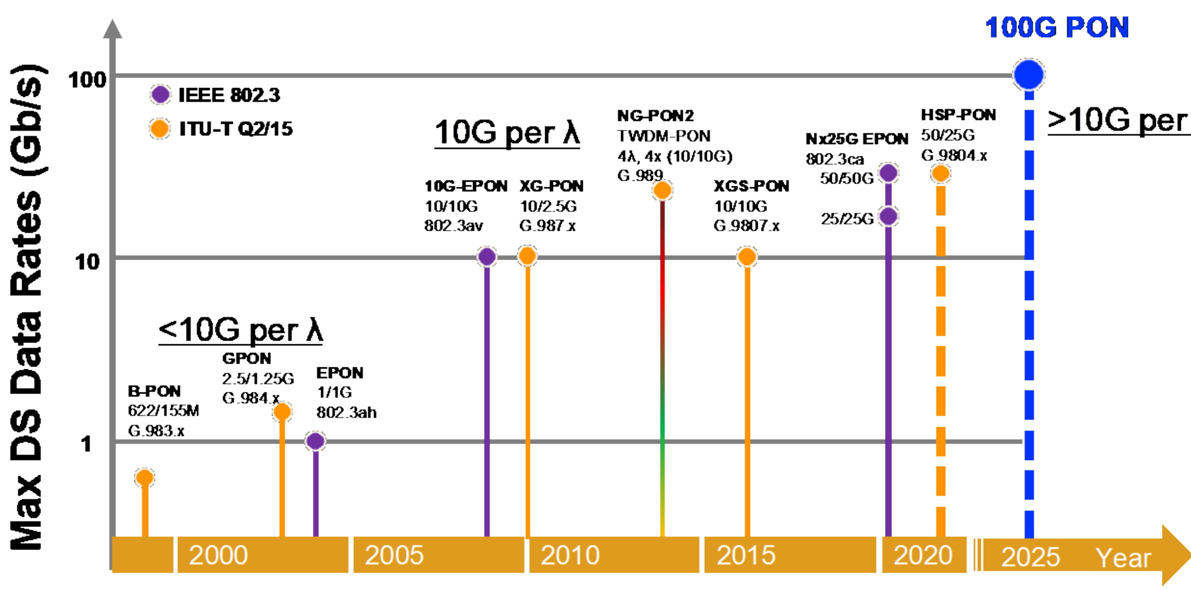


Figure 1 – Standardized PON Evolution

The development of PON systems over the past 20 years has resulted in two families of standards: ITU-T Question 2/Study Group 15 (Q2/15) and IEEE 802.3 Ethernet working group, as shown in Figure 1. Guided by the telco-led Full Service Access Network (FSAN) Group, the ITU-T PON systems are defined primarily in ITU-T recommendations, which cover the system and architecture, physical medium dependent (PMD), transmission convergence (TC), and management layers. The IEEE PON systems are defined by a combination of PMD and data link protocols in IEEE 802.3 while the management/system layers are defined in IEEE 1904.

The G.983 asynchronous transfer mode PON (APON) and broadband PON (BPON) were the first standardized ITU-T PONs in late 1990s with a line rate of 155 Mb/s to 622.08 Mb/s symmetrically. The next PON was the most widely deployed gigabit PON (GPON), standardized as ITU-T G.984 in 2003. The GPON speed was extended to 2.5 Gb/s in the downstream. The maximal reach is 20 km, with a maximal split ratio of 1:64. The Ethernet PON (EPON) is the first type of PON standardized by the IEEE in 2004 as 802.3ah. Data are transformed by Ethernet frames with the line rate of 1.25 Gb/s symmetrically, maximal reach of 20 km, and a split ratio of 1:32. For 10G line rate per wavelength PON, the 10G EPON standard was released in 2009 as 802.3av with 10.3125 Gb/s symmetrical line rate. Then next-generation PON (XG PON) was standardized in 2010 as ITU-T G.987, and the speed was increased to 10 Gb/s downstream and 2.5 Gb/s upstream. The next-generation PON stage 2 (NG-PON2) was standardized in 2015 as ITU-T G.989 with TWDM architecture. The NG-PON2 supports 4–8 wavelengths with broadband speed of 10 Gb/s per wavelength and 40-80 Gb/s aggregated capacity over a single fiber. The next-generation symmetric PON (XGS PON) is a symmetric version of XG PON with 10 Gb/s line rate for both downstream and upstream.

Going beyond 10 G line rate per wavelength, the IEEE 802.3ca Nx25G EPON Task Force recently defined a system based on 25 Gb/s line rate [2]. The initial objective was to standardize a 100G-EPON by bonding four 25 Gb/s wavelength channels together and was scaled back to a 2 × 25 Gb/s system in November 2017 as neither the technological maturity nor the market needs were present. On the ITU-T side, in 2021, a suite of G.9804 Recommendations or G.hsp was developed in the ITU-T for a 50 Gb/s line rate PON system with a vision of laying the groundwork for future ITU-T PON systems. Common transmission convergence (ComTC) layer in G.9804.2 is defined in a line rate (with fundamental line rate of 12.4416 Gb/s and line rate factor of 1, 2, 4…N to form the nominal line rate 12.4416 x N) agnostic of transmission rates, number of operating wavelength channels, and signal modulation and thus applicable to future TDM and TWDM PON systems [3].

For each generational PON development, operating over deployed ODNs and coexisting with legacy PON systems are two essential system requirements because ODNs are the biggest investment, and they have a lifetime much longer than technology cycle. These requirements can minimize the infrastructure cost and ease a smooth and non-disruptive migration towards new PON system. In comparison, the physical (PHY) layers in ITU-T and in 802.3 are largely equivalent because they both need to support similar operators' ODNs and leverage the common optoelectronic components and devices. The PHY layer generally handles the line rates, coding, forward error correction (FEC), wavelength plan, transceiver optical characteristics, ODN loss budget, reach, and coexisting systems.

All these standardized PONs employ simple intensity-modulation and direct-detection, IM-DD technology with non-return-to-zero (NRZ) format. Standardization of early generation PON was fairly straightforward. Between each adjacent generation, the main considerations were about increasing the data rate, higher launched power, or better FEC to fulfill a 29-dB or higher loss budget, which is the basic requirement for coexistence with legacy PON or reuse the deployed ODN. As shown in Figure 2, 25G EPON adopted low-density parity-check (LDPC) coding at the bit error rate (BER) threshold of 10^{-2} instead of keeping (Reed-Solomon) RS coding of XGS-PON at 10^{-3}. It is expected that 50G PON will further improve the coding gain by using soft-decision LDPC. It is envisioned that 100 Gb/s per wavelength and beyond will be required in the future to meet continuously growing bandwidth demands. To reach 100 Gbps, IM-DD OLT and ONU transceivers are required to be more advanced, and a much higher degree of complexity compared to previous generational PONs. analog to digital converter (ADC) and digital to analog converter (DAC), and digital signal processing (DSP) unit are required to mitigate or equalize bandwidth limitation penalty, device linearity, and transmission impairments. A high launch power from a range of 8 dBm to 11 dBm is needed potentially with optical amplifiers on both OLT and ONUs for IM-DD 100G PON to stay within the required power budget. Achieving such a high launch power at an ONU side is still too challenging in the upstream. In addition, fiber dispersion causes significant penalties for high-baud-rate signals. Coexistence with traditional PON services makes it challenging to find a suitable transmission wavelength window in the O-band. Therefore, for increasing the data rate for a single wavelength, limited sensitivity will become too challenging for the 100G TDM-PON to meet the required power budget by using direct detection in the O-band, not to mention extended power budgets to cover the long-reach or high-density applications.

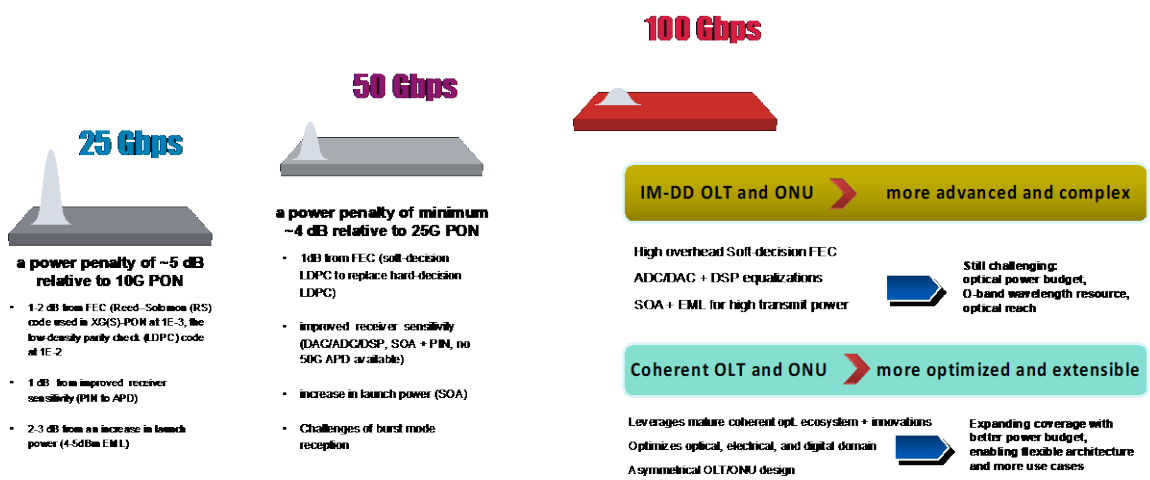


Figure 2 – Technolog Options in 100G PON

Coherent optics, on the other hand, more easily reaches 100Gbps because it divides the speed into 4 lanes, two polarizations each with amplitude and phase makes technology operate at 1/4 of the line rate [4]. Coherent optics, a game-changer optical fiber transport technology, has completely transformed optical transmission systems and enabled a widespread upgrade and new deployment of DWDM networks to speeds of 100 Gbps, 200 Gbps, and 400 Gbps per wavelength. Over the past decade, coherent optics has moved beyond its long-haul application origins to metro networks and now it has been introduced into access networks. Employing coherent optics in a PON offers many advantages. Coherent PON (CPON) is like traditional PON with point-to-multipoint topology over passive ODN. However, CPON uses multi-dimension modulation and coherent detection to provide longer reach and higher split ratio with improved optical power budget.

Compared to alternative direct-detect solutions that just use amplitude to represent the signal, only one dimension, coherent optical solutions (shown in Figure 3) use a high-power local laser source as a reference to achieve linear conversion of the optical field instead of optical power used in direct detection. This enables modulation and detection using four independent degrees of freedom, including amplitude and phase in two polarizations. With a local oscillator, significant coherent gain is provided along with wavelength selection without the need of an optical filter. Additionally, power fading induced by chromatic dispersion in direct-detection system is no longer an issue because of optical field recovery in coherent detection. All these features coherent optics bring to optical transport systems, enable greater modulation efficiency and receiver sensitivity. Coherent detection for short-haul networks enables a superior receiver sensitivity that allows for extended power budget. Its high spectral efficiency enables dense WDM (DWDM) and lead to higher capacity channels and fewer optical ports providing operational simplicity that may lead to overall network savings. Moreover, the multi-dimensional signal recovered by coherent detection provides additional benefits to compensate linear transmission impairments such as chromatic dispersion (CD) and polarization mode dispersion (PMD) and its most efficient use of fiber spectral resources results in more optical spectrum available for future use and enables future network upgrades using multi-level advanced modulation formats [5].

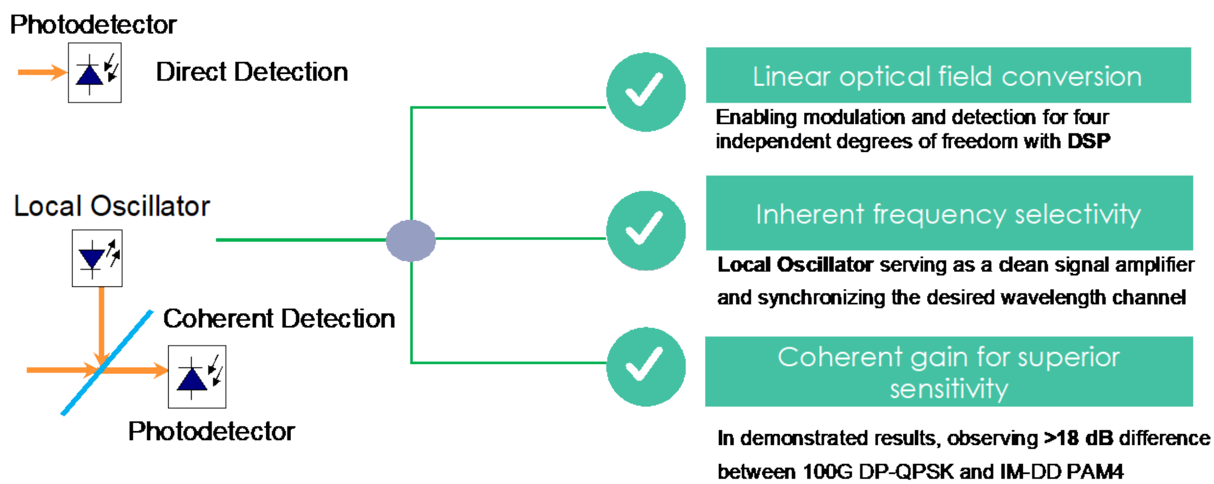


Figure 3 – Technology Comparison: Coherent Optics vs. IM-DD

2. CPON Deployment Scenarios and Use Cases

Leveraging its high sensitivity and powerful digital equalization of fiber transmission impairments, CPON offers unprecedently high degree of flexibility in terms of transmission distance and split ratio. Figure 4 shows measured 100G CPON split versus transmission distance topology options along with derived 100G target topology options after adding commercial implementation margin. CPON enables the service provider with significant flexibility on the network topology and reach [6]. Depending on different deployment scenarios, one can choose either very high split ratio at short reach, i.e., 512 split at 20 km transmission distance in Case 1, or low split ratio at longer reach, i.e., 16 split at 80 km transmission distance in Case 2 for rural applications. A hybrid mode in Case 3 that combining various split ratio at different transmission distances can also be achieved, i.e., a CPON port is first tapped at 20 km with a 90/10 passive splitter to support 64 splits, then tapped at 40 km with a 75/25 passive splitter to support 32 splits, finally at 80 km it supports another 8 splits. Case 3 represents the distributed CPON architecture to optimize optical power delivery over passive ODNs. The ample link margin enables flexible deployment of distributed CPON architectures where optical couplers with optimized coupling ratios can be used in a distributed fashion as the need for CPON connectivity is geographically dispersed. Each coupler diverts a fixed or adjustable portion of the CPON signal to a local splitter with the number of ports suitable for the demand of local CPON ONUs. As traffic and penetration evolves, the coupling ratios need to be adjusted. Incorporating adjustable and remotely controlled couplers enable automation and streamline operations.

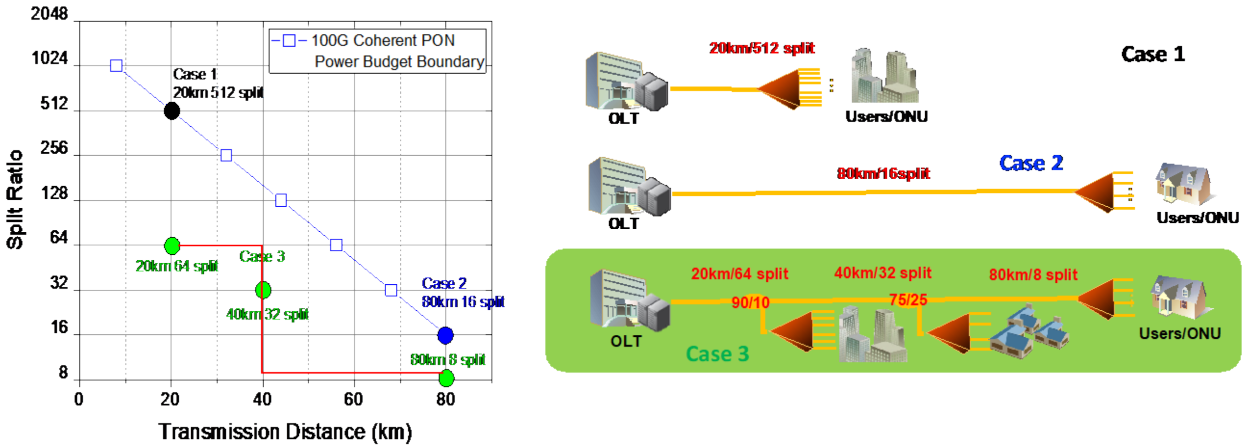


Figure 4 – Split Ratio and Transmission Distances for 100G CPON link

With the increase of CPON ability in higher capacity, longer reach, and higher split ratio, its applications are now extended to support many more optical connections. These include the new radio access network for the high-capacity x-haul transport of 5G and beyond 5G mobile networks, enterprise and business, access aggregation architecture, and even to data centers' aggregated connections. All these present new opportunities as well as challenges of a single platform for convergence of broadband wired and wireless access networks.

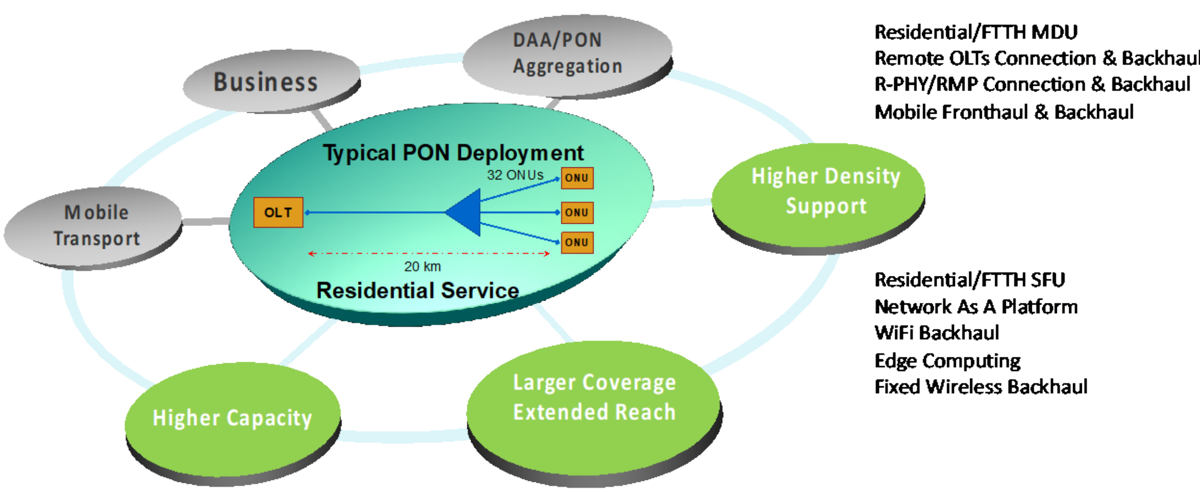


Figure 5 – Extended CPON Use Cases

CPON supports the use case of fiber-to-the-home (FTTH) connectivity. This includes direct fiber connection to either multiple dwelling units (MDUs) or single-family units (SFUs), as shown in Figure 5. CPON offers high density connectivity in densely populated areas, or long link distance connectivity in rural areas and other sparse/lower-penetration environments. In greenfield FTTH deployments without existing services, CPON deployment would ease operations in future years. In brownfield FTTH deployments with existing IM-DD PON, a CPON network could be overlayed using Coexistence modules (CEx), allowing the operator to gracefully migrate certain customers to increase revenue opportunities or lower congestion for other customers on the ODN. Network operators have wireline networks extending to multiple network edge devices that connect to end points such as residences, enterprises, or wireless access points. Links connecting edge devices consolidate at an aggregation node and are transmitted on a single optical link to a Hub/CO. CPON can be used to support back-haul connectivity to the aggregation node. The aggregation node, for example, can contain multiple remote OLT (R-OLT) devices, which moves the OLT out of the Hub/CO to the aggregation node location that is located close to ONUs. This Remote OLT case could be an important bridge for applications where the distance exceeds IM-DD limits, but where the capacity does not yet exceed the offerings of an IM-DD PON service. The aggregation node can also contain Remote PHY devices (RPDs) and Remote MAC-PHY devices (RMDs), to support distributed Converged Cable Access Platform (CCAP) architectures which offer operators great flexibility and low-cost deployment benefits.

Another use case for CPON is to provide mobile x-haul services. For example, CPON can be utilized to provide base station connectivity and carry back-haul traffic in 5G RAN. CPON can also carry traffic from the mid-haul/front-haul segment of 5G RAN. In this use case, beside meeting peak capacity requirement, CPON will be designed with reduced system latency leveraging low latency MAC mechanism for example, to meet the low latency requirements of 5G RAN.

In addition to FTTH, aggregation connectivity and mobile x-haul, CPON also supports a wide range of existing or emerging applications. For example, CPON can provide access point connectivity to carry Wi-Fi traffic or support fixed wireless back-haul and provide radio connectivity to carry fixed wireless traffic. CPON can serve to connect the users to edge computing nodes/devices located at the Hub/CO sites or provide connectivity from Hub/CO sites to edge computing platforms such as edge nodes near end users/subscribers. Furthermore, a point-to-multipoint local network infrastructure such as Passive Optical Local Area Network (POLAN) can leverage CPON to deliver data to multiple end users within campuses or buildings. CPON can also be adopted in emerging applications such as IoT-based Smart City, or Industry 4.0 Smart Factory, providing connectivity to many sensors and smart devices.

3. CPON Key Technology Development

Despite the numerous advantages offered using coherent optics in next-generation PON systems, major engineering challenges associated with CPONs for access applications remain. The coherent technology in a long-haul optical system utilizes best-in-class discrete photonic and electronic components, such as state-of-the-art digital-to-analog converters (DACs)/analog-to-digital converters (ADCs) and DSP ASIC based on the most recent CMOS process. These solutions are over-engineered, too expensive, too big, or too power-hungry for the access PON. Cost is the first challenge that must be resolved to introduce coherent optics into access networks. A PON is eventually directly connected to end users and is therefore highly sensitive to the cost of the optical and electrical components used in the network because of the enormous market involved. Therefore, the lasers, modulators, coherent receivers, and DSPs in an access network must be optimized to lower the complexity, cost, and power consumption. Meantime, it is worth noting that the total cost of ownership (TCO) should be considered here instead of single device or equipment. Coherent optics fiber spectrum reclamation not only alleviates the pressure to retrench new fiber, but also the low transmit power of coherent optics leads to the ability in placing a larger number of optical carriers on a single fiber strand. Looking at this from an overall system cost perspective, the usage optimization of fiber resources leads to a lowest cost per bit transport [7].

The cost of coherent detection can be broken down into several parts: the laser source, transmitter, receiver, and DSP. The first three parts are mainly optical and electrical components that can be simplified in many ways. In long-haul transmission, laser sources on both the transmitter and receiver sides are generally expensive, high-quality, narrow-linewidth (typically less than 300 kHz) external cavity lasers (ECLs). Basically, two laser sources are needed in one transceiver, including one signal carrier and one LO. One solution for cost reduction is to use fewer lasers in the ONU. Using a remote laser source from the centralized OLT for each ONU would reduce the overall cost by distributing the laser cost over the whole network. Lower cost distributed feedback (DFB)/distributed Bragg reflector (DBR) lasers, with linewidths of higher than 1 MHz, can also be introduced in coherent systems with minimal impact in performance for access applications [8-9].

Another major simplification is related to the transceiver, especially on the receiver side. A full field optical coherent receiver is typically used in long-haul transmission systems and consists of four pairs of balanced PDs (8 PDs) with polarization and phase-diversity homodyne coherent detection. Consequently, four ADCs are required for signal processing. This setup could be simplified by using fewer PDs. The use of heterodyne coherent detection can halve the number of required balanced PDs, ADCs, and associated TIAs. The system could be further simplified by removing the polarization-diversity receiving system and using polarization scrambling or a special polarization-time block coding method [7].

Therefore, coherent systems traditionally have come at a greater cost, but through access specific re-design, significant simplification and reduction in power consumption can be achieved. In this section, a few potential key technologies developed for CPON application are discussed.

3.1. Optical Phase Modulation

As modulators with low Vpi are developed, a simpler modulator design becomes an attractive alternative to traditional IQ modulators. An optical QAM coherent modulator could be implemented with a single-phase-modulator by directly modulating the laser to vary the amplitude, thus trading modulator driver signal complexity with a lower optical loss present in nested IQ modulators. Figure 6 compares a traditional nested IQ modulator structure with a simplified modulator using single-phase-modulator per polarization.

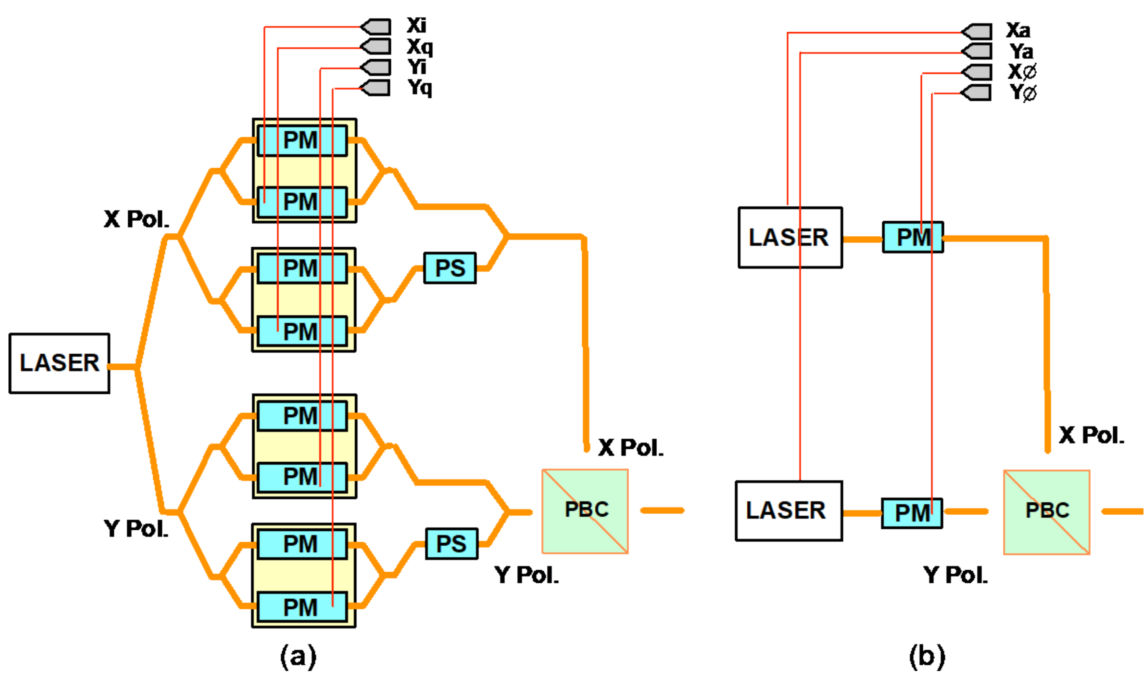


Figure 6 – Conventional IQ (a) and Simplified Optical Phase (b) Modulation Structures

This modulator alternative is simplified for a quadrature phase shift keying (QPSK) signal as no amplitude modulation drivers (Xa, Ya) are needed. We verify the results by testing the performance of 12.5 GBaud polarization multiplexed PAM-4 signal, which is equivalent to 12.5 GBaud polarization multiplexed QPSK after phase domain modulation. Phase domain multilevel signal modulation and post-equalization is verified here with coherent detection. The results of a signal in different stages of receiver-side DSP process are shown in Figure 7. Clearly, obvious phase domain inter-symbol-phase interference (ISPI) exists, with large phase fluctuations on four QPSK phases. By comparing Figure 7 (d) and (e) or comparing Figure 7 (c) and (f), we can see significant improvements.

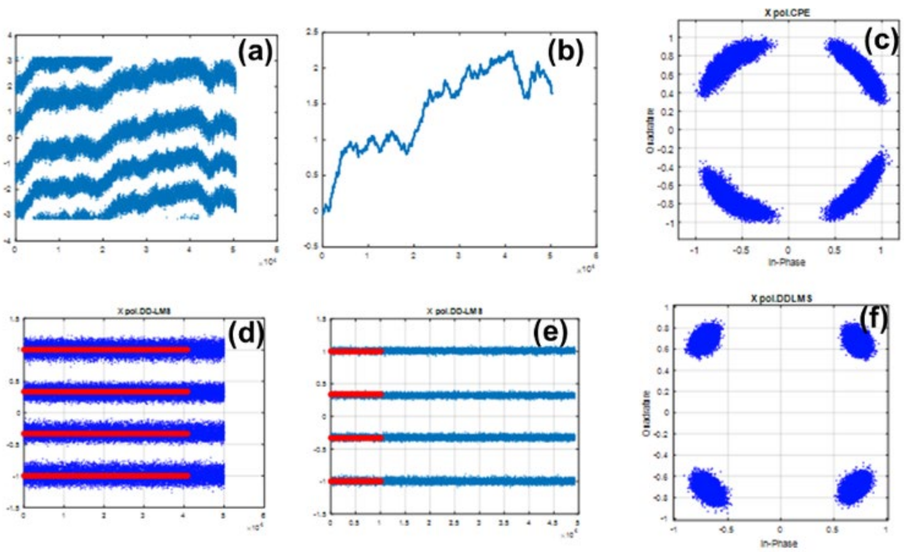


Figure 7 – Signal in Different Stages of Receiver-side DSP Process. (a) optical signal phase after frequency-offset estimation; (b) estimated optical signal phase noise; (c) QPSK signal constellation without phase domain equalization; (d) corresponding phase of QPSK signal in (c) mapped back to PAM-4 signals; (e) equalized PAM-4 signals after phase domain post-equalization; (f) QPSK signal constellation with phase domain equalization.

3.2. Simplified Carrier Phase Recovery (CPR)

In conventional CPR process, the independent phase estimation is performed for both polarization signals respectively. L-tap symbols are used for the center Symbol Sn+L/2 phase estimation based on 4th power Viterbi-Viterbi (VV) CPR or Blind phase search (BPS) algorithm as shown in Figure 8, where Sn is the n^{th} received symbol. As an example, for a QPSK signal with four phase states, the received complex symbols are first raised to the 4th power to remove modulation and make sure that only the phase noise is present. The Sn+L/2 is then added to N predecessors and successors to average the estimated phase. Because the phase varies over the range of 2π, the estimated phase must, therefore, be "unwrapped" to provide a continuous and unambiguous estimation of phase. After the phase "unwrapping", the compensation of an estimated phase error is performed with respect to the received complex symbols.

In the simplified CPR process for the hardware-efficient DSP flow, two steps are proposed. phase noise estimation is firstly performed at only single polarization direction and then shared with the second polarization signals as shown in Figure 9. Data-aided or blind estimation methods is then used for the fixed phase rotation estimation & recovery of the second polarization signal. In this way, only one dynamic phase noise estimation is performed, which is time varying with high computation complexity.

Fixed phase rotation estimation is a one-time process and the computation complexity is negligible when compared to dynamic phase noise estimation.

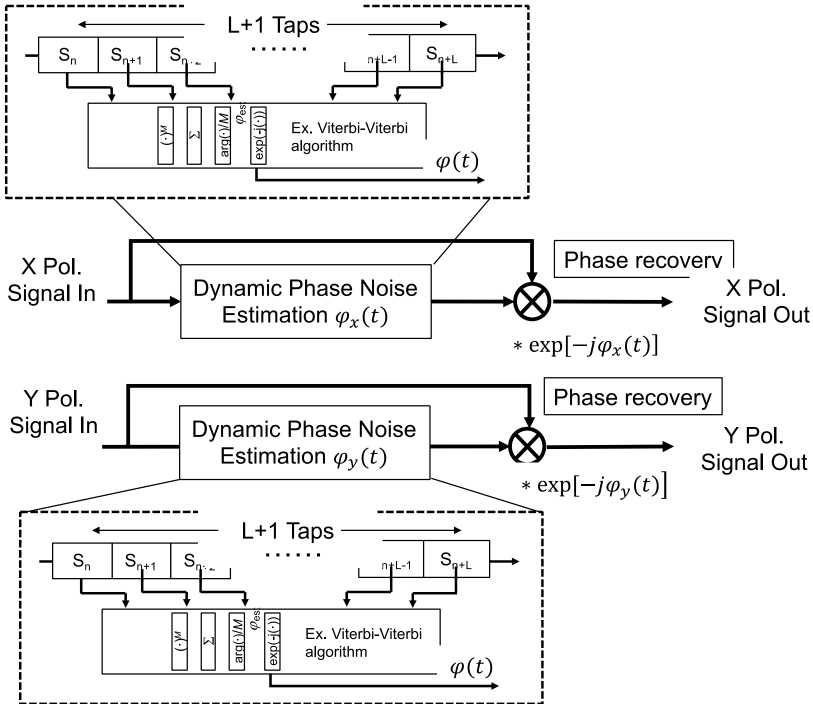


Figure 8 – Conventional CPR Process

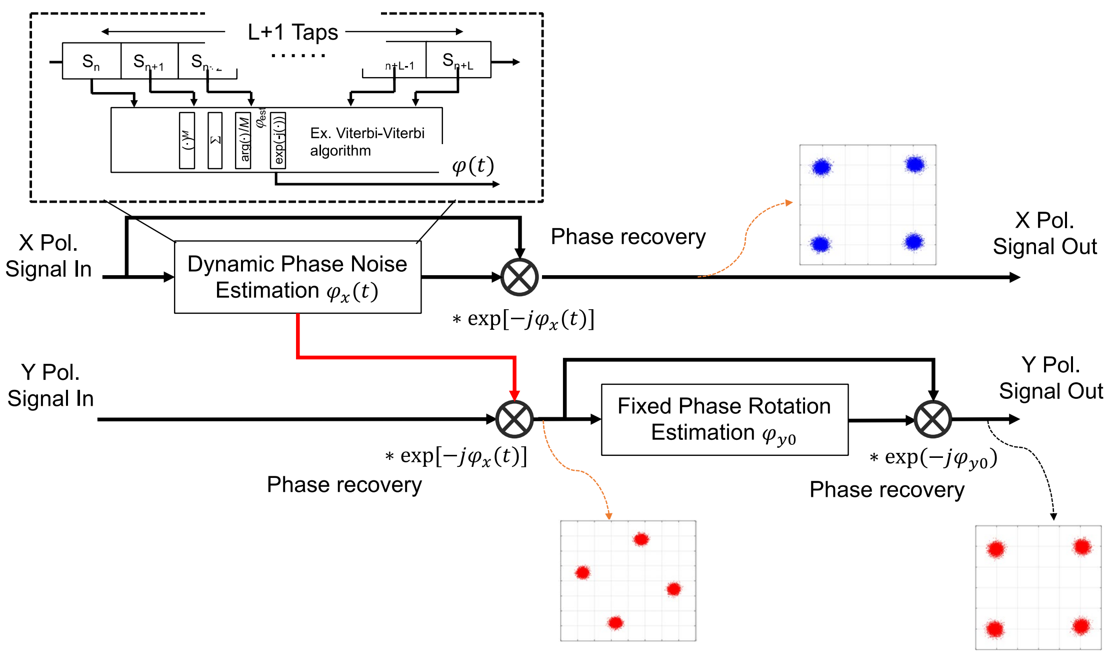


Figure 9 – Simplified CPR Process

Figure 10 shows the conventional and simplified CPR results. In the conventional algorithm (a), the independently estimated dynamic phase noise for X and Y polarization has the same phase evolution with a fixed phase offset. Since the independent phase noise from fiber nonlinearity is rather small at access distance, the phase noise in the two polarizations shows the same behavior except the fixed phase rotation. Figure 10 (b) shows the effectiveness of the simplified CRP process in the simplified DSP flow with the use of one polarization phase estimation result and fixed phase rotation for the other polarization.

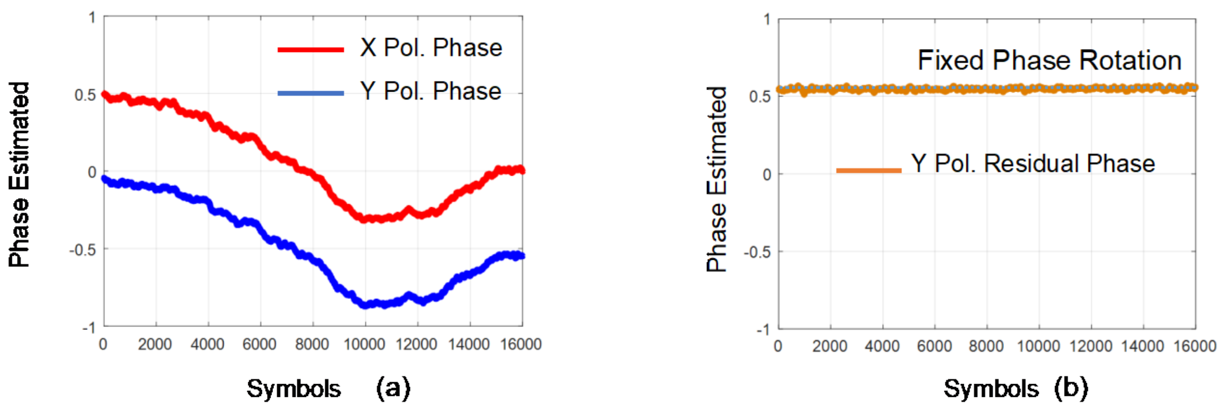


Figure 10 – Phase Estimation Results for Two Polarizations

Figure 11 (a) shows BER performance with different fixed phase rotation estimation methods. It is clearly seen that training sequence (TS) and blind estimation have very similar performance in the condition of fixed receiver power at -38.3 dBm. It also shows that 64 symbols of TS or average window size shows the converged results for fixed phase rotation estimation. Figure 11(b) demonstrates the optical power sensitivity comparisons with conventional and proposed CPR methods for both QPSK and 16QAM signals. The results show the simplified method can apply for different modulation formats and no obvious performance degradation is observed by using fixed phase rotation estimation compared to conventional methods.

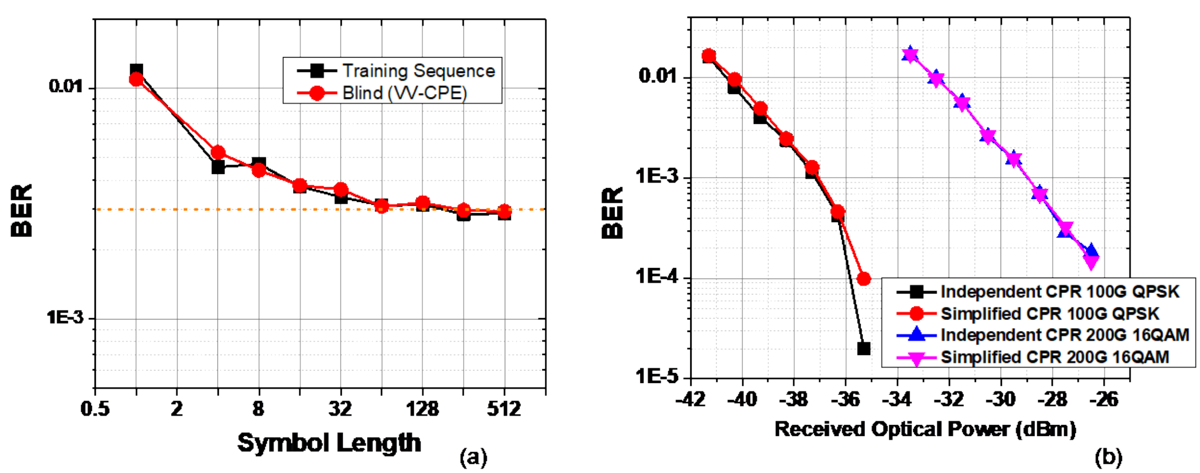


Figure 11 – BER Performance Comparisons

3.3. Preamble Design and Burst Signal Processing

One of the key challenges for CPON is the realization of upstream coherent burst-mode detection when coherent optics is brought to point-to-multipoint connection with a TDM fashion. Burst-mode coherent detection generally includes burst-mode linear amplification and burst mode DSP. Burst-mode amplification is required to deal with different signal power levels and enlarge the dynamic range. As considerable challenges are still associated with coherent receivers with burst-mode linear TIAs, optical burst-mode preamplification is an effective method of leveling burst signals before these signals are sent to coherent receivers via electrical, optical, or power control of local oscillator. Meanwhile, scheduler knowledge of which ONU is transmitting can also allow receiver to anticipate power level adjustment needed and ranging process can also be used to have the ONU pre-amplify Tx-burst so that it arrives at the OLT receiver at the desired level to alleviate some of the burden on the receiver.

Burst-mode DSP and an efficient preamble design at the receiver side are needed in addition to optical power control. The acquisition time for signal recovery at the coherent burst-mode receiver must be sufficiently short to improve the upstream efficiency. Specially designed preambles and fast DSPs have been reported. In pilot-aided time-domain estimation, a low-complexity widely linear compensation method is used to compensate for the IQ imbalance and burst-mode DSP based on precalculated finite impulse response (FIR) filter coefficients have also been demonstrated to shorten the acquisition time.

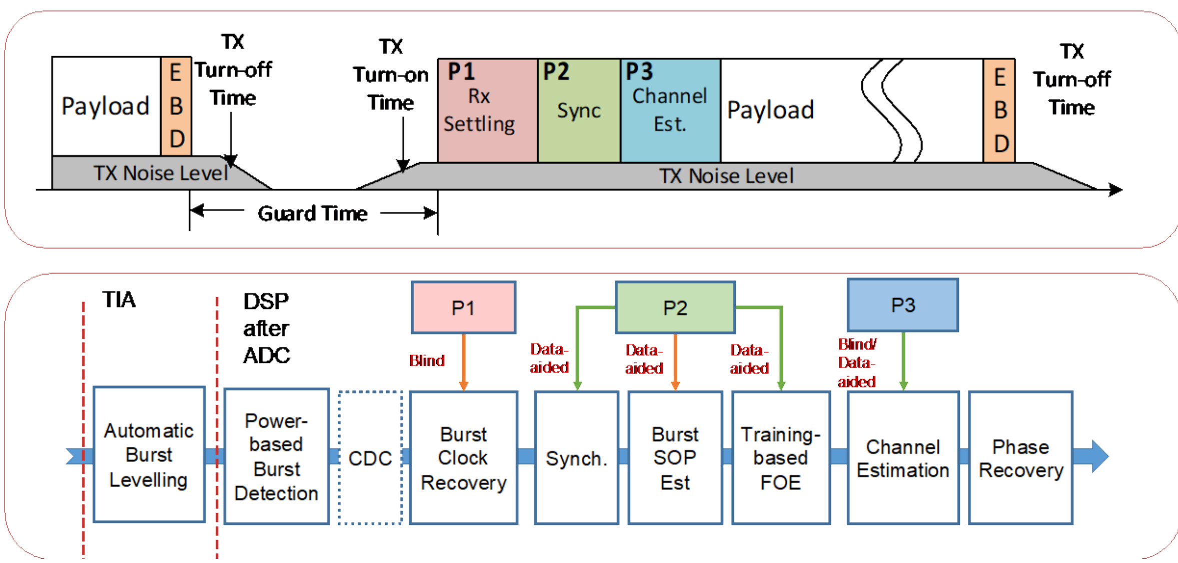
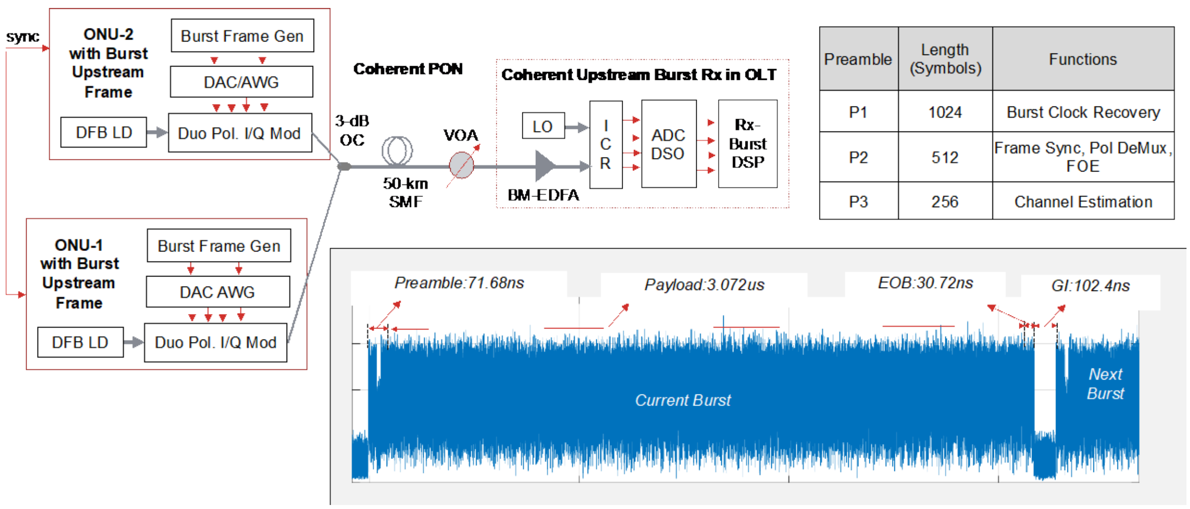


Figure 12 – Preamble Design and Coherent Burst Signal Processing

Figure 12 is a schematic showing the principle of the burst frame structure and upstream burst-mode signal recovery functions for a TDM CPON [10] with different synchronization patterns. Although the general concept is taken from the existing PON standards, most of the preamble patterns and related subfunctions are specially designed for dual polarization coherent bursts. Here, we consider the most complex case in which the optical signals are modulated and multiplexed on the phase, polarization, and amplitude. The proposed preamble consists of three sync patterns, P1, P2, and P3. Based on nearly equally distributed QPSK symbols, P1 is designed for receiver settling with burst-mode amplifications. P1 is also designed for burst clock recovery. P2 is designed for data-aided DSP synchronization functions, including frame synchronization, synchronization, and frequency synchronization (frequency offset estimation). In the design, 2 x N conjugate symmetric symbols are used to demonstrate the feasibility of efficient preamble design and signal processing, where three DSP functions share the same preamble to reduce the overall preamble length. Based on low-order training symbols (e.g., QPSK symbols), P4 is designed for adaptive channel equalization. Based on the information of the state of polarizations (SOP) estimated by P2, the inverse of the Jones matrix can be utilized to reduce the convergence time of adaptive channel equalization. Finally, the payload process can be simplified using the information from the proposed preamble. High-order modulation formats can be used in the payload block. Finally, the order of these preamble patterns and burst mode DSP functions may differ from that shown in Figure 12, depending on the algorithms used.



Preamble	Length (Symbols)	Functions
P1	1024	Burst Clock Recovery
P2	512	Frame Sync, Pol DeMux, FOE
P3	256	Channel Estimation

Figure 13 – Experimental Verfications for Coherent Burst System

Based on above preamble design and burst-mode DSP, we set up the experimental demonstration of coherent upstream burst detection in 100-Gb/s/λ TDM CPON, as shown in Figure 13. To evaluate the performance of upstream burst signal detection, two synchronized ONUs are running separately. At the ONU-side, the burst frames of 25-GBaud PDM-QPSK with the proposed preamble and structure as described in Figure 12, are generated by the 80-GSa/s arbitrary waveform generators (AWGs). Then the generated burst frames are fed into the dual-polarization I/Q modulators with four drivers for optical signal modulation. Here, we use a tunable DFB laser at 1550-nm wavelength with a linewidth of ~1-MHz as the laser source in each ONU. After modulation, the burst signals from ONU-1 are combined with a dummy signal from ONU-2 by a 3-dB optical coupler (OC). To avoid collision, the burst frames from two ONUs with same setup are staggered. Through the automatic bias-control and synchronization between two AWGs, the burst signal from one ONU is only coupled with the null signal from the other ONU.

The combined burst signals are then transmitted over 50-km single-mode fiber. The received optical power is controlled by a variable optical attenuator (VOA) for BER test. At the OLT-side, a burst-mode EDFA is used for signal pre-amplification. The pre-amplified signal is mixed with local oscillator (LO) in an integrated coherent receiver (ICR) for coherent detection. A tunable ECL at 1550m-nm is used as LO in OLT, and its linewidth is < 100-kHz. After coherent detection, the received signals are sampled by an 80-GSa/s scope and then processed via the offline burst-mode DSPs described in Figure 12. The detected power waveform of burst frame is shown in Figure 13 with the detailed configuration, and the summary of preamble unit length and functions is that P1, P2 and P3 have 1024, 512 and 256 symbols, respectively. Therefore, each burst frame contains a total preamble length of 71.68 ns (1792 symbols), a payload of 3.072µs, an end of burst (EOB) of 30.72 ns. A guard interval time of 102.4 ns is used to separate bursts. It is worth mentioning that the coherent preamble obtained is lower or comparable with preambles used by the different flavors of IM-DD PON, meaning that efficient preambles were achieved despite the dual polarization and IQ constellation complexity characterizing coherent transport.

4. Conclusion

This paper presents ITU-T and IEEE PON evolutions, the progress and limits of current intensity modulation and IM-DD PON technologies, and the major drivers and use cases for longer reach and higher split CPON. The high-level architectural requirements are discussed, such as the distributive optical taps for efficient power delivery, coexistence of generational PONs. This paper also provides the technology options to simplify the coherent OLT and ONU for cost reduction, and future PON upgrade strategies for different cable operators.

CableLabs® announced the launch of the CPON project in May 2021 toward the goal of future proofing cable's access architecture. The objective of the project is to initially develop specifications for 100G passive optical networks and devices that are multi-vendor interoperable, that coexist with existing infrastructure, and that can cost effectively be deployed at scale.

As reviewed in this paper, CPON demonstrates significant performance improvement, it can offer 10 times capacity compared to 10G PON and with the increase of 16 times in split ratio or 4 times in transmission distance, from 20km to 80km. Leveraging such capabilities and CPON synergies with existing HFC architectures, will allow CPON to significantly expand its capabilities beyond traditional residential deployment to support convergence needs at the network edge, from DAA aggregation, mobile x-haul, optical LAN, all the way to future fiber to the MDU and home.

It is worth mentioning the significant advantages that CPON brings beyond speed. Transitioning to coherent transport from IM-DD or analog optics results in a more efficient use of the optical wavelength spectrum. One can use one CPON channel instead of using ten 10 Gbps PON channels, which allow the operator to reclaim optical fiber spectrum just like they did years ago in the coaxial domain when transitioning from analog to digital video. Port reduction at the hub location is another key advantage when transitioning from 10 Gbps systems to 100 Gbps system as it reduces real estate in the router/switch and simplifies operation. The reach that CPON enables leads to pervasive all passive networks, forgoing the need in placing cabinets with repeaters to when link distances exceed 20 km and the operational overhead associated in maintaining and powering repeaters. The split and reach combinations possible with CPON results in great flexibility and homogeneity in the use of technology, meaning one technology that can be used for all services. CPON is a technology that is in a nascent stage with a lot of room to grow.

It is believed that CPON technologies can carry the cable industry for 20, 30, or 40 years into the future, just like DOCSIS has done since 1995!

Abbreviations

AN	aggregation node
b/s	bit per second
CEx	coexistence element
CO	coherent optics
CPR	carrier phase recovery
DSP	digital signal processing
FEC	forward error correction
HFC	hybrid fiber coaxial
IM-DD	intensity modulation and direct detection
IQ	in-phase and quadrature
MUX	multiplexer/demultiplexer
ODN	optical distribution network
OLT	optical line terminal
ONU	optical network unit
PHY	physical layer
PM	phase modulation
PON	passive optical network
QAM	quadrature amplitude modulation
QPSK	quadrature phase shift keying

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