

Coherent Passive Optical Networks: Why, When, and How

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Abstract—While the capacity of the next-generation access network is expected to be 100Gb/s and beyond, coherent optics is going to be a logical choice for the physical layer as the currently used intensity-modulation/direct-detection (IM/DD) technology will fail to meet the required power budget of such high line-rate systems. In this article, we present an overview of necessities, timeframe, and technological challenges for the future passive optical network (PON) utilizing coherent technology.

INTRODUCTION

The bandwidth requirement in access networks is increasing tremendously due to advanced services and applications such as 5G/6G mobiles, 4K/8K video streaming, cloud computing, and so on. A passive optical network (PON) is a cost-effective approach to deliver the high data-rate fiber access service to the user. The IEEE recently standardized a 25Gb/s line-rate PON [1] and the ITU-T has just standardized a 50Gb/s line-rate PON [2]. Moving forward, the research for the future generations of PON has already started considering a data rate of 100Gb/s and beyond [3].

Given the historical timeline of PON standardization, as shown in Fig.1, at least a four-fold increment in capacity is observed between two adjacent ITU-T PON generations. Considering the same trend, the 200Gb/s PON is a natural choice for the next generation of fiber access beyond 50G-PON. Even though 100Gb/s PON is also being researched [4], only two-fold increase capacity might not be sufficiently future-proof considering the huge investment by network operators in access deployment.

So far, all standardized PON solutions are based on simple optical intensity modulation (IM) and then

a direct-detection (DD) receiver that detects only the power of the incoming optical field. However, such an approach does not seem to be feasible for PON at 100Gb/s+ due to limited receiver sensitivity. Thus, IM/DD will not meet the required loss budget of the deployed optical distribution networks (ODNs). As an alternative, coherent technology, which enables modulation and detection of amplitude, phase and polarization of optical signal, is a promising candidate for such high-capacity future access.

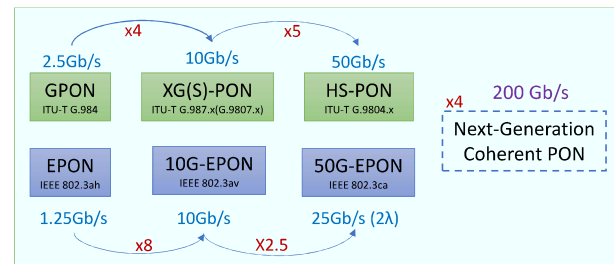


Fig.1: The line-rate progression in different PON standards of ITU-T and IEEE.

To date, all PON systems are fixed rate but flexible line-rate might be an interesting feature for future PON. Since each user experiences a different channel, due to the point-to-multipoint nature of the PON structure, and there is a variable bandwidth requirement for different use cases, the throughput of each class of user can be optimized by exploiting flexible line-rate. In this paper, we focus on the 200Gb/s line-rate future PON, however, with a flexible modulation format, the proposed transceiver can support lower line-rate such as 100Gb/s with higher link budget.

In this article, first, we discuss the rationale behind the use of coherent optics for next-generation PON. Then, we speculate about the possible coherent PON

(Coh-PON) technology development timeframe. Next, a possible system architecture exploiting Coh-PON is presented. After that, the technological challenges and possible solutions of using coherent optics for PON are explicitly discussed. The key challenges considered are the reduction of cost and complexity of the subscriber-side optical network unit (ONU) while ensuring robust detection of burst-mode signals at the optical line terminal (OLT) in the network operator’s central office.

WHY COHERENT OPTICS FOR PON?

The commonly used direct-detection receiver detects only the intensity of the incoming optical signal. With increasing line-rate, the receiver sensitivity decreases due to more integrated noise within the larger signal bandwidth and the penalty due to fiber chromatic dispersion also increases, which leads to a very limited power budget.

In a direct-detection receiver, the linear channel impairments convert to nonlinear due to the square-law detection process and this makes it difficult to fully compensate with digital signal processing (DSP). On the other hand, a coherent receiver enables linear conversion of the optical field facilitating detection of the signal amplitude, phase, and polarization. It offers several key benefits in the PON application.

Firstly, it gives an improved receiver sensitivity and thus an adequate power budget with a modest transmitting power. The enhanced sensitivity is achieved through pure amplification of the signal through the local oscillator (LO) power. The increased power budget could extend the reach and/or support a larger number of connected users. Coh-PON is a good fit for supporting both rural areas and reducing the amount of outside plant in urban areas. Furthermore, the data-rate requirement of 5G and beyond mobile xHaul could be as large as a few hundreds of Gbit/s, which is quite challenging for conventional PON. Coherent optics could be a promising solution here.

Secondly, being a linear receiver, Coh-PON allows the use of advanced multi-level modulation formats by exploiting four degrees of freedom for data transmission (in-phase and quadrature modes in two polarization states), and enables efficient use of DSP algorithms. These in turn allow the use of higher-order modulation formats with lower bandwidth transceiver components. DSP techniques can further

relax the bandwidth requirements of receivers. For example, a digital pre-emphasis at the transmitter can mitigate the penalty due to the limited bandwidth of transceivers. This comes at the expense of additional signal processing and the associated power consumption. The fiber chromatic dispersion can be fully compensated using DSP and thus the linear transmission penalty can be neglected. The DSP-based perfect chromatic dispersion compensation also allows operation in the low fiber attenuation wavelength band (around 1550nm), giving even extra margin of power budget, and an easy co-existence with the legacy TDM-PON through wavelength overlay.

Thirdly, coherent detection has inherent frequency selectivity nature through the choice of LO wavelength. This is particularly advantageous in wavelength division multiplexing (WDM)-PON where the channel of interest can be detected without any optical filters.

TIMELINE FOR COHERENT PON

Herein we present a hypothetical timeframe for Coh-PON based on the history of past PON standardization and deployment. It takes 5 to 10 years between two generations of standardized PON systems. Furthermore, typically ~8 years are needed between deployments of each generation. Therefore, considering the earliest conceivable time interval, the coherent generation of TDM-PON could be standardized ~2026. With 2-5 years before deployments, following the finalization of standards, the operation of Coh-PON might start ~2028. Early applications might be for lower volume business, services and then gradually move through medium to high volume applications such as 6G xHaul and residential services (FTTH) respectively. Considering this scenario, a speculative, and optimistic, timeline for Coh-PON is illustrated in Fig.2.

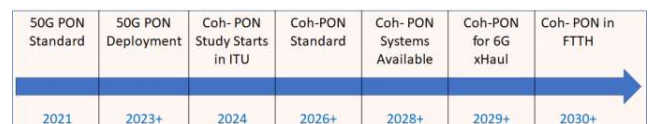


Fig.2: Possible PON technology evolution timeline.

REFERENCE ARCHITECTURE OF COHERENT PON

A PON is a point-to-multipoint network in which an OLT at the network operator’s central office is

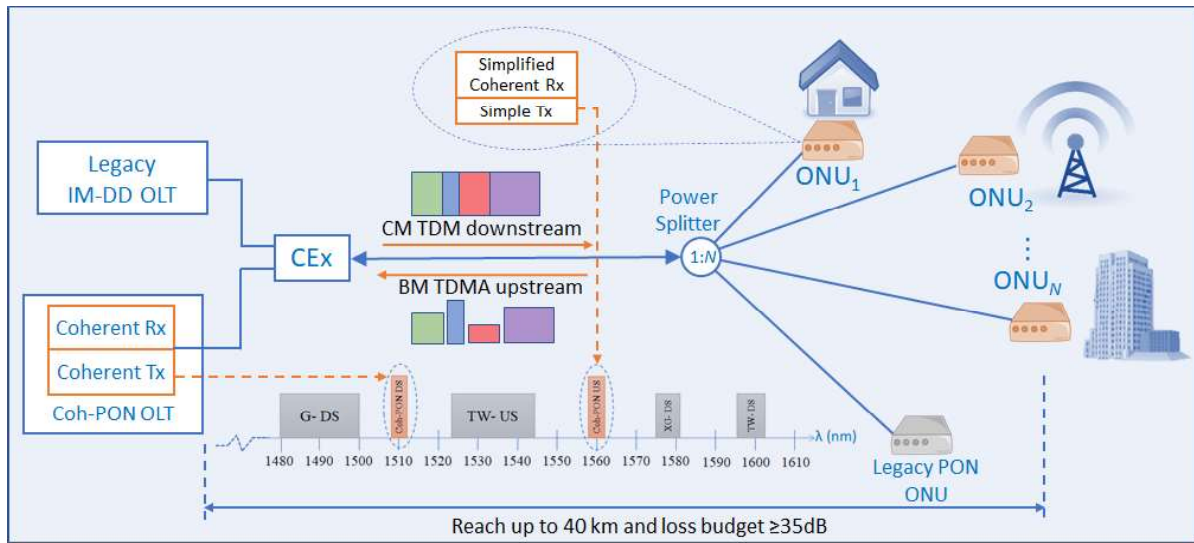


Fig.3: Schematic reference architecture for a TDM-PON employing coherent technology serving different end user services. The TDM-PON downstream and upstream data types are illustrated along with a possible transmitter wavelength assignment for the two directions in Coh-PON. (Rx: receiver, Tx: transmitter, BM: burst mode, CM: continuous mode, CEx: coexistence element, US: upstream, DS: downstream, G-: GPON, XG-:XG-PON, TW-: TWDM-PON, Coh-PON: coherent PON).

connected to many ONUs on the subscriber side through a passive optical distribution network which includes transmission fiber and one or more optical power splitter stage. Typically there is no in-line amplification and fiber is used bidirectionally with different wavelengths employed in each direction. For efficient sharing of bandwidth resources, three PON structures are considered in standards: time division multiplexed PON (TDM-PON), WDM-PON, and time and wavelength division multiplexed PON (TWDM-PON) [2]. Among them, due to the highly cost-effective approach, TDM-PON is the most widely deployed to date (>95% Gigabit-class and 10 Gigabit-class PONs). Thus, single wavelength per direction TDM-PON is the main focus of the rest of this paper.

A reference architecture for a Coh-PON is shown in Fig.3. Here TDM is used in the downstream direction with continuous mode operation and TDMA in the upstream with burst-mode operation. On the OLT side, a conventional dual-polarization (DP) coherent transceiver is used whereas, on the ONU side, we propose a simplified coherent receiver and the simplest of amplitude-modulated transmitters e.g. based on an electro-absorption modulated laser (EML). The rationale behind this approach is that the ONU is a more cost-sensitive

unit than the OLT as the cost of the latter is shared by all subscribers on the PON.

Since the ODN construction is the major cost portion of a PON deployment, it is desirable that the ODN can be re-used for Coh-PON. Therefore, the current loss budgets of legacy PON systems need to be maintained also for Coh-PON. Furthermore, while upgrading to Coh-PON, the already deployed PON technologies are expected to coexist on the same fiber. Therefore, the Coh-PON needs to operate using different wavelengths to the existing PON technology. It can be seen in Fig.3 that three possible wavelength windows for Coh-PON in the S, C, and L bands (1500nm-1524nm, 1544nm-1575nm, and 1581nm-1596nm) can be considered. All of these three windows have the benefits of having low fiber attenuation. The C-band option may be preferable for the ONU because of mature and high-volume optical transmitter component availability. Selecting the S-band for the OLT can ease the separation of the counter-propagating Coh-PON signals and blocking of the co-existing PON signals. A possible wavelength plan for Coh-PON is shown in Fig.3 with the downstream at 1510 ± 2 nm and upstream at 1560 ± 2 nm. Note that this proposal also does not overlap with any wavelength used by IEEE PON technology. Additionally, it is assumed that the RF

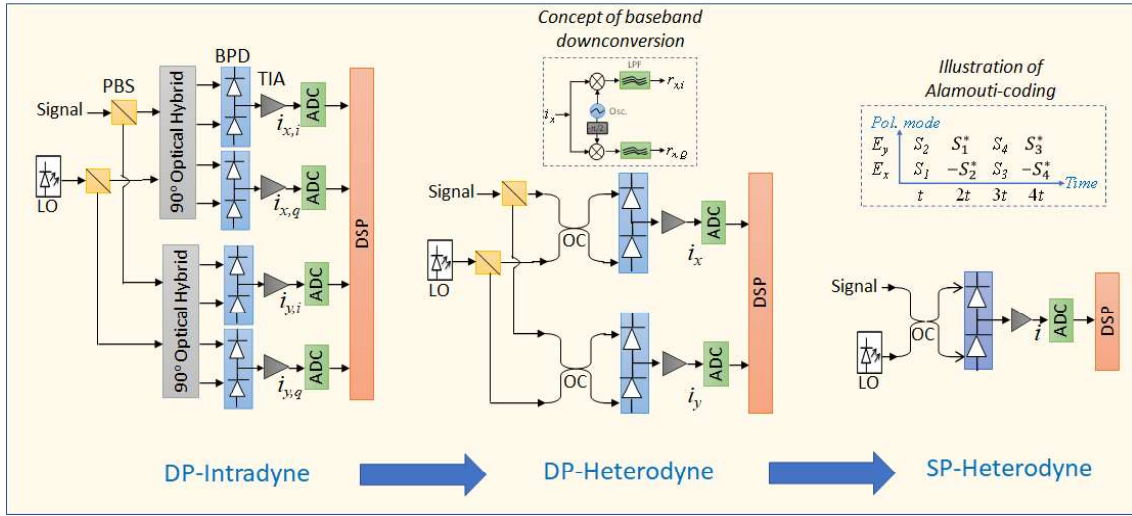


Fig.4: The concept of coherent receiver simplification steps. Compared to DP-intradyne receiver, DP-heterodyne one replaces 90° optical hybrid with a simpler optical coupler and other optoelectronic components are halved. Single-polarization realization further reduces half of the components. (LO: local oscillator, PBS: polarization-beam-splitter, BPD: balanced photodiodes, TIA: transimpedance amplifier, ADC: analog-to-digital converter, DSP: digital signal processing, LPF: low pass filter, OC: optical coupler).

video wavelength (1550nm-1560nm) deployed by some network operators will be no longer used as video services move to internet streaming.

LOW-COMPLEXITY RECEIVER FOR DOWNSTREAM

A typical DP-coherent intradyne receiver used in core networks is comprised of two polarization beam splitters (PBSs), four balanced photodiodes, four transimpedance amplifiers (TIAs), and four analog-to-digital converters (ADCs) as shown in Fig.4 [6]. The complexity, cost, and power consumption of such a receiver are too high for application at the ONU side of a PON. Therefore, at present, the stripped-down coherent receiver approach is an active research topic.

The number of optoelectronic components can be halved by using heterodyne detection and baseband downconversion at the DSP unit (as shown in the inset). Also, the optical 90° hybrid is replaced by a much simpler 3-dB optical coupler. However, such a simplification comes at the cost of increased receiver bandwidth requirements, at least twice that of intradyne detection.

The receiver can be further simplified by using single-polarization detection and sacrificing spectral efficiency. We can construct a single-polarization heterodyne receiver with only a 3-dB coupler, a single balanced-photodiode, and one ADC as shown

in Fig.4. However, such simplification requires a larger bandwidth, higher ADC sampling rate and more processing power. Also, performance of such receiver is sensitive to polarization fluctuation of the incoming signal. To make this receiver polarization-insensitive, a polarization diversity technique can be implemented at the OLT transmitter side instead of at the cost-constrained ONU. There are several techniques to achieve this: Alamouti coding in two polarization tributaries, differential group delay (DGD) pre-distortion and polarization scrambling [7]. Among them, the most robust polarization-insensitive operation can be achieved using the Alamouti coding approach where the transmitted symbol pairs in two polarization states in a time slot are mutually orthogonal in the next time slot as shown in the inset of Fig.4 [8]. It is important to note here that, the sensitivity performance of such a simplified receiver is close to that of a typical coherent receiver since there is less insertion loss between LO and photodiodes [9].

Fig.5 shows the simulation results for the power budget at an FEC BER limit of 10^{-2} as a function of launch power for the three aforementioned coherent receiver configurations considering 200Gb/s line-rate transmission at 1510nm with 16-QAM modulation format and 40 km reach. Thermal and shot noise terms are considered in the receiver *i.e.* the

dominant sources of noise for unrepeated transmission. At the shot noise limit, with sufficiently high LO power, a similar sensitivity is expected for both DP intradyne and heterodyne receivers with ideal front-end components. However, we consider a LO power of 10dBm to keep the ONU cost low and with such power level, thermal noise has considerable contribution. Therefore, the heterodyne receiver has a better performance compared to intradyne one mainly due to having less thermal noise for the reduced number of TIAs. The single-polarization heterodyne receiver has the least thermal noise, however, it provides less power budget than the DP case due to the inherent sensitivity penalty for doubling the symbol rate for the same line-rate. Nevertheless, we can achieve a maximum power budget of 38.05 dB with the simplified heterodyne receiver satisfying the E2 class loss budget (*i.e.* 35dB) of ITU-T standards.

There are other simplified coherent architectures available in literature such as single-ended DP heterodyne receiver (known as Glance receiver), and the use of 3x3 coupler with intradyne and heterodyne detection [10]. However, considering that the packaging cost of the receiver, including the subsequent ADC, scales with the number of interfaces, the single-polarization heterodyne receiver seems to be the simplest and most cost-effective solution.

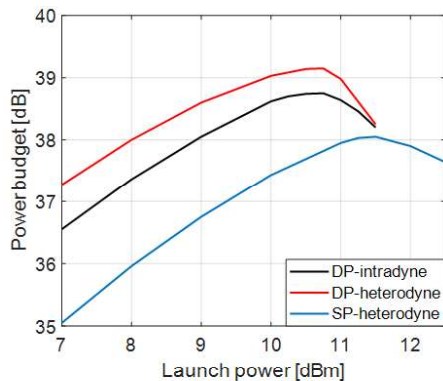


Fig.5: Power budget at $\lambda=1510\text{nm}$ as a function of launch power for different coherent receiver configurations with 200Gb/s line-rate and 40km reach. (DP: dual-polarization, SP: single-polarization).

The other key challenge of ONU receiver design is to implement a low-complexity DSP algorithm to keep the power consumption down. The sampling rate of ADC is one of the main factors of the power

consumption of DSP. However, with sub-Nyquist sampling and advanced DSP, the signal can still be recovered with a reasonably low penalty [11]. As for the DSP algorithm, the adaptive filter for equalization is a power-hungry unit [11]. Its complexity can be reduced in several ways, for example, by implementing it in the frequency domain or hybrid time-frequency domain [6], separating the polarization filter from the static filter [12], multiplier free update such as sign-sign constant modulus algorithm [6]. Another challenging DSP block for Coh-PON is the carrier recovery algorithm due to its complexity. Since the ODN reach in PON is typically limited to a couple of tens of kilometers, the polarization mode dispersion (PMD) is expected to be low. Hence, it is possible to estimate the phase noise in one polarization and then use the value for the other polarization channel [12].

With the significant advancement of photonic integration in the last decade, various active and passive optical components now can be integrated in a single device. Thus it is expected that the coherent module will benefit from this progress to enable a substantial reduction in cost, footprint, and power consumption within the timescale for Coh-PON applications.

CHALLENGES FOR COHERENT UPSTREAM

The use of a conventional DP-IQ transmitter at the user end for upstream transmission is cost-prohibitive and a key limitation. The IQ modulator used in such a transmitter requires complex bias control and monitoring. Also, it has a large insertion loss requiring an optical booster amplifier which is undesirable at the ONU side. In the case of heterodyne detection, the LO can conceivably be shared with the upstream transmitter, however, such an approach makes it challenging to implement a low-cost diplexer. Also, we need a high power LO (and thus more costly), otherwise the ONU receiver sensitivity will degrade significantly due to reduced LO power for sharing with upstream transmitter. Furthermore, a spectral guard band would be needed between the downstream and upstream, increasing the bandwidth requirement of the ONU receiver. Therefore, one reasonable technology choice is to use a conventional EML or DML to generate intensity-modulated signals such as binary non-

return to zero (NRZ) and pulse amplitude modulation (PAM). At the OLT, a coherent receiver is still necessary to achieve high sensitivity and thus the required link budget.

The main challenge of the OLT coherent receiver is to detect the burst-mode signal effectively. Firstly, the receiver needs to cope with a dynamic range up to 20dB. Such a wide dynamic range severely degrades the signal-to-noise ratio (SNR) of the received signal due to two factors. The first one is the limited linear region of TIA. If TIA gain is optimized for the weak burst signal, the strong bursts are clipped due to the saturation of TIA degrading its performance. The second issue is the inadequate ADC vertical resolution. If the ADC's full-scale range (FSR) is adjusted to detect strong burst, the weak burst does not use the full vertical resolution and suffers from large quantization noise. To cope with the wide dynamic range, burst-mode optical amplifiers such as burst-mode erbium-doped fiber amplifier (BM-EDFA) or burst-mode semiconductor optical amplifier (BM-SOA) or electrical burst-mode TIA can be used [13]. The schemes with such amplifiers usually have two cascaded amplifier stages with independent automatic gain control (AGC) where the first stage attenuates the strong bursts and the second one sets all the bursts at the same amplitude levels.

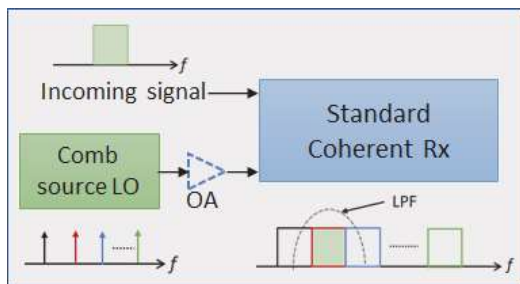


Fig.6: Principle of using comb source as LO for the coherent receiver (OA: optical amplifier, LPF: low pass filter).

Another key challenge is to design a reliable and efficient, but short, preamble of a burst frame [14]. The incoming upstream signals from different ONUs arrive burst by burst and typically have different signal powers, state of polarization (SOP), degradation due to fiber transmission, and timing. The receiver DSP needs to adapt to those changes within the short preamble time. In particular, adaptive equalization has to converge very quickly.

This can be achieved by setting initial taps weights with predefined values that give a relatively good performance for all ONUs or by using precalculated equalizer setting for different ONUs in the discovery process and handover or by utilizing fast converging adaptation algorithm such as the ones based on variable step size techniques.

A further challenge in burst-mode coherent detection is the frequency locking of the LO to the received signals from different ONUs. The laser wavelength of low-cost packaged transmitters like DML or EML at ONU side may drift even a few nm. A promising solution to cope with such wavelength drift is to use a wavelength comb source as the LO [15] as shown in Fig.6. This approach avoids the need for fast LO tuning and allows the ONU laser to drift within the range of the comb source spectrum. An optical amplifier may be used with the comb source to increase the power per comb line to operate the receiver near the shot noise limit. The principle of such comb LO-based detection is also depicted in Fig. 6. The channel spacing among the comb lines is chosen approximately equal to the bandwidth of the upstream signal. In the coherent detection process, the signal beats with one of the comb lines. The received signal is then passed through a low pass filter in the digital domain to recover the signal spectrum. It may be noted that, a practical and mature comb source device is not yet available for application as the LO of a coherent receiver. Promising approaches using photonic integration will need research and development.

Aside from the TDM/TDMA approach, other multiplexing options have recently been investigated for Coh-PON including digital subcarrier multiplexing (SCM) and time and frequency division multiplexing (TFDM) [5].

CONCLUDING REMARKS

In the last decades, coherent technology has been widely deployed in core networks. Recently, its use has been transferred to short-reach applications such as data center interconnect (DCI) with the introduction of 400G ZR. Still, there are few key limitations left for its deployment in access such as higher cost, power, and footprint of the coherent module. Given that with the advancement of technology, such problems will be solved in near

future by co-design and co-packaging of optics, RF, and DSP ASIC in a pluggable coherent transceiver. Therefore, coherent technology can be a natural choice for next-generation PON-based access networks at 100Gb/s per wavelength and beyond.

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