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[Invited Tutorial]

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Overview of High-Speed TDM-PON beyond 50 Gbps per Wavelength using Digital Signal Processing [Invited/Tutorial]

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The recent evolution of Passive Optical Network (PON) standards and related research activities for physical layer solutions achieving bit rates well above 10 Gbps per wavelength (λ) is discussed. We show that the advancement toward 50, 100 and 200 Gbps/λ will for sure require a strong introduction of advanced digital signal processing (DSP) technologies for linear, and maybe nonlinear, equalization, and for forward-error correction (FEC).

We start by reviewing in detail the current standardization activities in the International Telecommunication Union (ITU)-T and the Institute of Electrical and Electronics Engineers (IEEE), and then we present a comparison of the DSP approaches for traditional Direct-Detection (DD) solutions and for future Coherent Detection approaches.

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1. Introduction

In this paper, we review the recent research and standardization steps towards the development of higher-speed PON physical layer, following the evolution for bit rates well above 10 Gbps/λ.

The paper is organized as follows. We begin with a section (Section 2) that provides an in-depth overview on the evolution of PON market and standardization. Within this overview section there is a specific focus on bit rate standardization for 25 and 50 Gbps/λ, showing the resulting progressive introduction in these standards of DSP functionalities. The following section (Section 3), details DSP-based solutions that have been proposed recently at the research level for 100 Gbps/λ direct-detection (DD) PON. This is then contrasted in the next section (Section 4) with approaches for 100 Gbps/λ and beyond based on Coherent PON, including means of simplifying coherent receivers with a view of reducing cost and DSP power consumption. We then conclude in Section 5 with a final discussion on the ongoing PON trends.

2. Overview of PON standardization

A. Overview of market status and deployment

The deployment progress of PON is remarkable. Since its initial mass deployments began circa 2004, the technology has grown to approach a billion users worldwide by 2021. It now surpasses digital subscriber line services in number of users, and this will only increase as more networks are upgraded worldwide by their operators. Through this development, system standards have been very important, due to the special practical and commercial characteristics of broadband access. In short, access networks are a huge investment, and are composed of millions of cables and associated equipment distributed over a wide area. This makes low cost, high volume, and supply-chain reliability key aspects for PON systems. By standardizing the system, multiple vendors can build compliant products that multiple operators can use in an interoperable way. Over time, this has been shown to reduce costs through efficiencies of scale and free market economics. It makes the business more stable since there are multiple vendors and operators, and therefore no single entity is critical.

Over the last 20 years, ITU-T and IEEE have been very active in this field. In particular, the ITU-T study group SG-15 (question Q2) has standardized many PON systems [1]. The early systems like asynchronous transfer mode (ATM)-PON were almost experimental and never reached significant volume. The first system that had over 1 million users was broadband PON (B-PON, ITU-T G.983 series), due to its deployment in Japan and the United States [2]. However, B-PON was quickly overtaken by Gigabit PON (G-PON ITU-T G.984 series), and G-PON is the system that has taken PON to the billion level now [3]. G-PON delivers 2.5 Gbps downstream and 1.25 Gbps upstream. Its widespread adoption caused the industry to realize that the optical distribution network (ODN) is a huge investment that is intended to work for many decades. This directly led to the consideration of PON coexistence,

where multiple PON systems can operate on a single ODN, typically by using different wavelengths. From the G-PON system onwards, coexistence capability has been a key requirement.

In Fig. 1, we show a schematic of the PON standardization evolution since G-PON (and its IEEE counterpart: Ethernet PON (E-PON)), and possible future paths. The follow-on system from G-PON was 10 Gbps PON, which was standardized in two versions: asymmetric XG-PON (ITU-T G.987 series) and symmetric XGS-PON (ITU-T G.9807 series) [4], [5]. While the standard for XG-PON was published in 2010, it only started to see strong deployment about 2016. The reason for this delay was due to the speed at which operators can adopt new technologies into their network. As such we see a 10-year cycle emerging between the deployment of one system to the next, with strong deployment of XG-PON coming a decade after G-PON. Beyond the PON world, we see that this cycle time of around a decade is also used in the wireless access market [6].

After the XG-PON system was completed, the PON research community turned to consider what is next, and a new standard that could deliver at least 40 Gbps was developed. It was called next generation PON 2 (NG-PON2) [7]. The design of NG-PON2 was the subject of a vigorous debate inside ITU-T, and there were many proponents of wavelength division multiplexing (WDM)-PON systems. The salient feature of initial WDM-PON is the replacement of the optical splitter in the ODN with an arrayed waveguide grating. This has the double issue that 1) it cannot coexist with the previous time division multiplexing (TDM)-PON, and 2) it requires the rework of the ODN. Either of these were considered as show-stoppers, and so the option of a pure WDM-PON architecture was discarded. Instead, the NG-PON2 work progressed to consider TDM-PONs of the necessary 40 Gbps capacity. At the time of standardization, 10 Gbps seemed to be the fastest signaling speed achievable with economical components. Thus, the NG-PON2 system would implement the time and wavelength division multiplex (TWDM) on four wavelengths in each direction [8], but confirming the use of traditional splitter-based ODN. This is described in the ITU-T G.989 series, which was completed in 2015. This work uncovered several interesting optical issues with multi-wavelengths PONs, including burst mode wavelength drift and out of band (OOB) optical interference [9]. It also introduced various mechanisms to tune and control the optical network units (ONUs). Unfortunately, the NG-PON2 system has not seen much take-up in the market for a variety of reasons. XG-PON was going into deployment just as TWDM-PON was being productized, and so it had to compete with this less expensive system. In the optical access ecosystem, all single wavelength PON standards up to now have specified a large wavelength tolerance for the lasers, to allow for the use of lower cost uncooled devices while a multi-wavelength system should have a tighter wavelength specification thus requiring temperature controlled lasers and, consequently, it would increase overall costs. Thus, NG-PON2 has not yet seen commercial success. It did however trigger the next step of PON standardization in IEEE 802.3, which led to defining new solutions for higher bit rates but on a single wavelength per direction, as will be explained in the next sub-section. This was also the "turning point" for the introduction of DSP in PON transceiver, which is the main focus of our paper.

B. ITU-T and IEEE standards for 25G / 50G

The IEEE started investigations of PON systems exceeding 10 Gbps in 2015. The operators driving this effort were the USA cable television networks. The situation that had developed over time was that the traditional telephone companies had focused on using ITU-T PONs, while the cable companies were using IEEE PONs. In 2015, the systems poised for deployment were XG-PON and 10GE-PON. To a large extent, this situation was very balanced, as XG-PON and 10GE-PON have almost
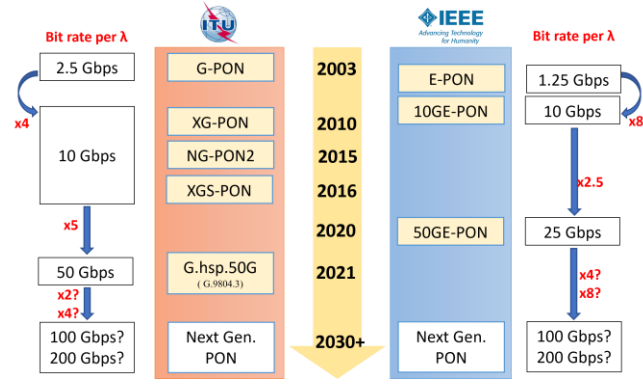

Fig. 1. ITU and IEEE PON standards evolution.

the same capacity and similar other characteristics. When the cable companies saw NG-PON2 standardized, this was somehow perceived as a threat, and something that required a response. Hence, the IEEE 802.3ca project was started to specify 100 GE-PON [10].

At that time, 25 Gbps/λ transmission technology was rapidly growing and becoming more cost effective. This is mostly due to its use in the 100 Gbps Ethernet optical interfaces for data center applications, which use four 25 Gbps wavelengths over a single fiber (100GBASE-LR4). This was achieved through the improvement of optoelectronic bandwidths as well as the use of the O-band which greatly reduced dispersion. At first glance, one might think that 100GBASE-LR4 optics could be reused also for PON, but this is not possible. LR4 optics operate over two fibers (PON is always one fiber), and the power budgets are dramatically different (the maximal extended reach ER4 budget is 18 dB, while PON requires about 30 dB). The 100GE-PON would require eight wavelengths in total, and it is rather hard to find all of these in the O-band. Moreover, the coexistence requirements with previous PON standards must be met, which takes away even more spectrum. This wavelength plan was so difficult that eventually the objectives of the project were reduced to 50 Gbps total capacity (50GE-PON), thereby requiring four wavelengths. The final plan defined two downstream bands and three upstream bands (the extra band required to support coexistence between 10GE-PON and 50GE-PON). The higher power budget was supported using a stronger low-density parity-check (LDPC) FEC code, more powerful transmitters, and better avalanche photodiode (APD) receivers [11], [12]. This standard was completed in 2020.

In parallel to this standardization effort, there was a lingering interest in single channel 25 Gbps PON (25G-PON). This system can be seen as a simplification of the 50GE-PON system, as it only supports one of the wavelength channels. There is a multi-source agreement (MSA) effort to help specify this kind of system. In that MSA, the protocol from G.9807.1 is merged with the simplified physical medium dependent (PMD) layer from 802.3ca [13]. This is likely the fastest single channel PON system that is possible without DSP for adaptive equalization. It should be noted that this system is not the subject of a standard. The 25G-PON system was proposed to ITU-T Q2 several times, but it was not agreed to move forward. Major operators did not see the need for a 25G system available in the near term.

While the 50GE-PON project was going on, there began to be signs that 50 Gbps transmission over a single wavelength was becoming practical. In 2016, ITU-T began a project to consider higher speed PONs, and this led to a formal recommendation project in 2018. This project took a more top-down approach, and thus started with the most basic operator requirements: coexistence, low cost, at least 4x capacity, and deployment circa 2025. Given this relaxed time horizon, the group selected 50 Gbps on a single wavelength in each direction. The line code

selected was non-return to zero (NRZ)-on-off keying (OOK), because it has the best loss budget despite its higher natural bandwidth requirements [11], [12]. The system attempted to reuse as much of the good results from the IEEE 802.3ca project: the wavelength and coexistence plan, and powerful FEC code were reused. However, the major divergence was in the assumption of the use of DSP to achieve 50 Gbps operation. At these high speeds one must assume that the transmission channel will have a non-uniform frequency response that must be equalized. DSP technology has become much more commonplace and low-cost, and that is expected to continue. The following Section 3 goes into detail on the use of DSP. The final result was the 50G-PON system, defined in the ITU-T G.9804 series, which was approved in 2021 [11].

C. Single versus multiple wavelength PON and higher speeds

At present, both ITU-T and IEEE PONs have made forays into the domain of multiple wavelengths, but in different ways. The NG-PON2 system has multiple wavelengths, but each ONU only uses a single pair of them. The 50GE-PON system has multiple wavelengths that are intended to work together at the ONU. However, in both cases, these systems have failed to live up to their promise because there is a simpler single wavelength system to compete with. This phenomenon is not new, and throughout the evolution of optical transmission the tradeoff between signaling speed and wavelength count has occurred. At any point in time, the industry will use the highest practical speed per channel and then use WDM to increase the capacity to whatever the application requires. As time goes on, the "highest practical speed" will increase, and so the use of multiple wavelengths changes.

In recognition of the changing situation, the ITU-T G.9804 series is intended to define a collection of higher speed PON systems. They all share the common requirements for PONs (G.9804.1) and a common transmission convergence (TC) layer (G.9804.2) which is scalable to higher bit rates and multi-channel operation. The first system is the 50G single channel system, which is defined in G.9804.3. The second system will be a multiple 50G channel system, which will be specified in G.9804.4. This system can be seen as the successor of the NG-PON2. However, unlike NG-PON2, G.9804.4 might see use if it becomes the most cost-effective way to deliver higher bandwidths over the PON medium. The deciding factor is whether the demand for greater than 50 Gbps system shows up before the availability of a single channel higher speed system.

The work on G.9804.4 is ongoing. One of the major decisions for the Q2 group is the choice of wavelength strategy. One of the advantages of the TWDM system is that each of the channels in the system can be a different data rate. The system can be upgraded on a channel-by-channel basis, much like the optical transport network. As it happens, the NG-PON2 system has a wavelength plan where the downstream channels are in the L-band, and the upstream channels are in the C-band. This works well enough for 10 Gbps per channel, and these bands have favorable coexistence characteristics; however, they present a problem for 50 Gbps operation.

There are two possible solutions to this issue. The first would be to define a new multi-channel plan in the O-band. The low dispersion there would allow DSP-supported intensity modulation (IM)-DD transmission, just as in the single channel system. However, this presents coexistence issues since the spectrum in the O-band is quite congested. It also spoils the incremental upgrade story that was so attractive for NG-PON2. The second solution would be to stay in the C and L bands, and shift to coherent optical transmission. Of course, once coherent techniques are used dispersion becomes an easy matter to correct, and they also bring higher sensitivity and longer range operation into view. That said, going coherent is yet another major step up in complexity and cost, just as going to tunable optics was considered

a "bridge too far" for the NG-PON2 system. To address this concern, a great deal of work has been done on the so-called "low cost coherent" technology. Currently there is a lot of work in this area for data center interconnect applications, so some of these techniques might become a commercial reality. The main of these will be reviewed in the Section 4 of this paper. The jury is still out on this fundamental choice for G.9804.4.

Looking further out, we could consider what the next step for single channel PONs might be, and the possible options are clearly 100 Gbps/λ (100G-PON) or 200 Gbps/λ (200G-PON), as depicted in Fig. 1. Following the mainstream 4x bandwidth scale, the next step after 50 Gbps would be 200 Gbps. Anyway, 100 Gbps per channel is a very popular design choice.

For 200G-PON, it is anticipated that coherent technology would be required, even if the system operates in the O-band, as dispersive effects become just too strong for IM-DD to cope with, while 100G-PON has been proved in laboratories to be possible also with IM-DD, though using advanced DSP. Our following Sections 3 and 4 will give an in-depth review on these two options.

3. PON using IM-DD solutions

A. Main modulation formats

All PON generations, including 50G-PON, have defined NRZ-OOK as modulation format. Other formats, such as quaternary pulse amplitude modulation (PAM)-4, duobinary (in its electrical and optical variants), carrierless amplitude-phase modulation (CAP) and multi-carrier techniques, such as orthogonal frequency division multiplexing (OFDM) and discrete multi-tone (DMT), were analyzed as alternatives during the development of 25G- and 50G-PON. All of them are more resilient than OOK to dispersion and bandwidth limitations, as shown later. However, OOK is simpler and less affected by device non-linearities. Moreover, its main advantage is its higher sensitivity, which is crucial to meet the demanding PON power budget.

The main alternative to NRZ-OOK has been duobinary (DB) modulation, which can be derived from the binary one with relative simplicity. In the conventional approach [14], three blocks are required to convert OOK into DB: a precoder, an encoder and a half bit rate (R_b) filter. At the receiver side, the duobinary signal is decoded back to OOK as follows: first, symbol decision is performed using a two-level slicer, producing a 3-level sequence $d(n)$, which is then passed through a modulus-2 block that directly decodes the signal applying the operation $x'(n) = \mathrm{mod}_2(0.5d(n)+1)$. The signal $x'(n)$ is the received version of the original bits before precoding. A well-known variant of the previous structure consists on replacing both the encoder and half-data rate filter at the transmitter by a 5-th order Bessel filter with a bandwidth of around $0.25 \times R_b$. Under some conditions, i.e. if the full IM-DD system bandwidth is $\sim 0.25 \times R_b$, the previous Bessel filter can be avoided, then
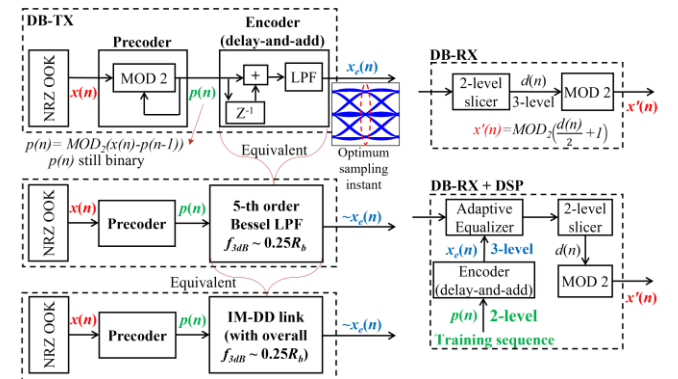
Fig. 2. Variants of duobinary (DB) at transmitter (TX) and receiver (RX) sides. LPF: Low-pass filter, MOD 2: modulus-2, Z^{-1}: one-symbol-delay.

simplifying the duobinary transmitter [14]. Furthermore, the $\sim 0.25 \times R_b$ bandwidth condition can be relaxed, if an adaptive equalizer is included, trained with the encoded duobinary signal [15]. The described duobinary variants are depicted in Fig. 2. We call the last variant, consisting on just a precoder at transmitter, as simplified electrical DB (EDB). The EDB has been widely analyzed [10], [16], [17], showing that it can achieve a higher tolerance to dispersion and bandwidth limitations than OOK. A back-to-back sensitivity penalty of EDB with respect to OOK of ~2.0 dB is present when the channel bandwidth is $>0.5 \times R_b$ [17]. However, for channel bandwidths less than $0.3 \times R_b$, EDB overcomes OOK, particularly if using adaptive equalization [17]. A similar situation occurs when introducing chromatic dispersion (CD), as described in sub-section 3.E.

PAM-4 was discarded as modulation format for 50G-PON due to an inherent high sensitivity penalty (>5 dB) with respect to OOK. However, for higher data rates, sticking with OOK seems unfeasible due to bandwidth limitation requirements in optoelectronic (O/E) devices. Then, PAM-4 seems the more doable option. In fact, all the datacenter ecosystem moved to PAM-4 above 50 Gbps. The worst sensitivity of PAM-4 can be compensated using more powerful FEC schemes (see sub-section 3.B) or optical amplification (as discussed in sub-section 3.C). Alternatives to PAM-4 are CAP and OFDM/DMT, which are spectrally efficient formats. At 50 Gbps, recent publications have shown that PAM-4, CAP and DMT have very similar performance when operated in O-band [18]. Then, PAM-4 is the best option among them since it is simpler. However, it was also shown in [18] that the dispersion tolerance of CAP and DMT is higher. Fig. 5 of [18] shows that PAM-4 stops working for dispersion values higher than 110 ps/nm, while CAP and DMT are able to tolerate around 130 and 140 ps/nm, respectively. Therefore, although at 50 Gbps in O-band (where worst case dispersion is around 77 ps/nm) CAP and DMT superior performance is not evident, when doubling the data rate to 100 Gbps (or higher values), the situation could be different, which is an open topic for research.

A vast literature is available for the application of OFDM and DMT as modulation formats in the area of PON (see for instance [19], [20]). However, none of these proposals ever reached the standardization or pre-commercialization level, likely for technical reasons associated to the high linearity requirements for the transmission and detection of OFDM/DMT signals, and for the intrinsic peak-to-peak limitations in optical IM-DD system which do not match well with the typical high peak to average power ratio of OFDM/DMT signals.

A simpler alternative to PAM-4 is partial response PAM-4 (PR-PAM-4) [21], [22], [23]. PR-PAM-4 can be obtained from a PAM-4 signal in the same way DB is coded from OOK. By adding a proper precoder at the transmitter, and a 6-level slicer and modulus-4 block at the RX, a simplified PR-PAM4 (SPR-PAM-4) structure can be designed [22]. SPR-PAM-4 is able to outperform PAM-4 under some practical conditions, as shown later.

B. Forward Error Correction (FEC) options

It is well-known that due to receiver noise, an increase in bit rate reduces the power budget for the same transmitted power. Some ways to increase the transmitted and/or the receiver power by means of optical amplification are discussed in sub-section 3.C. Another option to increase the power budget is the use of FEC. Starting from XG-PON, it was necessary to introduce FEC schemes to take advantage of their coding gain (translated into an optical power gain). For XG-PON and XGS-PON, relatively simple hard-decision Reed-Solomon (RS) FEC, for instance RS(255, 239), was widely used and led to a pre-FEC BER=10^{-3} threshold. A higher performance FEC has been defined for 50G-PON in G.9804 using LDPC codes, leading to a pre-FEC BER=10^{-2} threshold, as shown in the first line of Table I [24]. LDPC can be implemented as a hard decision FEC. Moreover, taking advantage of DSP introduction in

Table I. List of some LDPC variants, taken from [24].

N [bits]	K [bits]	M [bits]	S [bits]	P [bits]	Code rate	Input BER threshold*
17280	14592	2688	0	384	0.8444	1.0×10^{-2}
11520	9216	2304	5376	768	0.8000	1.1×10^{-2}
11520	8960	2560	5632	512	0.7778	1.3×10^{-2}
11520	8704	2816	5888	256	0.7555	1.6×10^{-2}
11520	8448	3072	6144	0	0.7333	1.9×10^{-2}

*Assuming NRZ over a binary symmetric channel, hard input FEC decoder providing a post-FEC bit error ratio $<10^{-12}$. Symbols: N – codeword length, K – information length, M – parity length, S – shortening length, P – puncturing length.

PON, they can be implemented as a more powerful soft-decision FEC. A list of different LDPC code variants is shown in Table I [24], showing that even more powerful FEC options can be selected for future PON physical layers above 50G-PON, allowing for a relaxed BER target of 1.9×10^{-2}, thus enabling a power budget increase. The list of LDPC options presented in Table 1 is obtained assuming the same mother code (the one defined for 50G-PON) to which shortening and puncturing was subsequently applied [24]. Other LDPC codes are available with even better coding-gain performance, even though typically at the expenses of longer coding blocks and thus higher complexity and latency.

Regarding the use of FEC in combination with adaptive equalization, it is important to take into consideration an additional optical power sensitivity penalty of ~0.45-0.6 dB with respect to the optical gain ideally expected for the LDPC FEC scheme, due a broadening of the distribution of the number of errors in a codeword (for hard-decision FEC) [25] and error correlation (for soft-decision FEC and decision feedback equalizer (DFE)) [26].

C. Semiconductor Optical Amplifier (SOA)- versus APD-based receiver

APDs were introduced to 10 Gbps PON to meet the power budget requirements. For 25G-PON and 50GE-PON, 25G-class APD with a bandwidth around 16 – 20 GHz were developed. However, APDs with enough bandwidth to support OOK 50 Gbps (and beyond) operation are not currently available. As explained in next sub-section, one alternative against this issue is the use of 25G-class APD in combination with techniques to counteract this bandlimited scenario. Another proposal consist on using PIN receivers with higher than 20 GHz bandwidth, already existing for the 50G datacenter products. Since a PIN alone is not able to achieve the required sensitivity for 50G-PON, adding a SOA as pre-amplifier is nowadays a popular alternative [12], [27]. SOA+PIN receivers are already in the market for the extended reach 100G-Ethernet solutions. Moreover, SOA is a small component that can be integrated with the rest of the optical receiver elements. Several works have analyzed the performance of SOA+PIN receiver for 50G-PON (and beyond), showing a sensitivity similar to that obtained with APDs, and in some cases even higher [28], [29].

The use of SOA has not only been proposed at the receiver side, but also as booster amplifier integrated with an electroabsorption-modulated laser (EML), to produce a high-power transmitter [30]. Currently, output powers of 10 dBm [31] and 11 dBm [32] can be achieved using this transmitter structure.

D. DSP techniques to combat bandwidth limitations

All generations of PON transceivers up to 25G-PON have used O/E devices with enough bandwidth to support NRZ-OOK modulation (i.e. more than 70% of the data rate) and, in this application scenario, higher cardinality modulation formats and equalization were not required.

During the development of 25 Gbps/λ PON, alternatives to the DSP-free approach were proposed. They aimed to re-use 10G-class O/E, especially the APD, counteracting the resulting bandwidth limitations by implementing duobinary modulation formats and/or equalization. Although the DSP-free 25G-PON approach was at the end preferred, due to O/E cost reasons, 50G-PON will be based on bandlimited devices and DSP-aided transceivers. Given the fact that ITU-T G.9804 decided to still keep the NRZ-OOK format, adaptive equalization at the receiver is one of the strongest proposals to deal with bandwidth limitations.

One of the simplest equalization alternatives proposed for 50G-PON is the feed-forward equalizer (FFE). The FFE structure can be implemented analogically, using continuous time linear equalizer (CTLE) [33], or fully-digital after analog-to-digital conversion. The digital approach provides higher performance at the expense of higher cost and power consumption in the application-specific integrated circuit (ASIC). Higher performance equalizer options, such as DFE and maximum likelihood sequence estimator (MLSE) mandates for a fully-digital DSP. The tolerance to bandwidth limitations using equalization at the receiver is limited by the noise enhancement issue. Using NRZ-OOK, a typical FFE can work with a tolerable power penalty (1 dB) if the system bandwidth is higher than $0.4 \times R_b$ [12], [17]. Moving to the EDB (see sub-section 3.A) approach, the tolerance to bandwidth limitations is higher: the power penalty remains below 1 dB for system bandwidth $>0.27 \times R_b$. Under more bandlimited conditions, the FFE power penalty starts increasing exponentially, and at some point the equalizer stops working.

DFE, a slightly more complex equalizer, overcomes FFE under more bandlimited conditions. For instance, for a 50 Gbps OOK transmission using an APD with 18 GHz bandwidth, a DFE with 10 feed-forward taps and 2 feedback taps provides a 4 dB gain as compared to an FFE with 10 taps [12]. A 1.5 dB gain of DFE over FFE is reported in an experimental 50G-PON OOK evaluation in [34]. Simulation results for 50G-PON OOK show a 7.5 dB gain of DFE using 20 feed-forward taps and 5 feedback taps over an FFE using 20 taps for an APD bandwidth of 12 GHz [15].

MLSE has in general a better performance than FFE [35] and DFE. However, a small advantage of MLSE as compared to DFE at a BER target of 10^{-2} for 50G-PON has been reported, for two independent experiments, in [12] and [34] . Therefore, the highest complexity of MLSE can prevent its use if DFE obtain a similar performance. More evaluations are needed to determine the conditions in which MLSE shows its superior performance.

Moving towards 100G- and eventually to 200G-PON, we can anticipate that the bandlimited operation will be more critical. By the time when these ultra-high capacity PON generation will be developed, it is expected to have broader bandwidth devices, even though, not enough to avoid equalization. 25G-class technology is already commercially available, while 50G-class is still under development. To forecast the performance of a 100 Gbps PON transmission using 25G- and 50G-class devices, simulation results are presented in Fig. 3, showing the power penalty of three modulation formats: PAM-4, SPR-PAM-4 and PAM-8 as a function of the transceiver bandwidth [22]. The zero-penalty corresponds to the PAM-4 unconstrained bandwidth case. Two equalization approaches are compared: FFE with 20 taps (FFE(20)), and DFE with 20 feedforward taps and 5 feedback taps (DFE(20,5)). Assuming 50G-class devices availability (i.e. having a bandwidth around 35-40 GHz), PAM-4 is the best format exhibiting a penalty of up to 1 dB in the range of 25 GHz to 40 GHz. In this region DFE does not provide any gain over FFE. The situation is different when using 25G-class devices (i.e. having a bandwidth around 16-20 GHz). Under these conditions, the use of DFE provides a gain over FFE using PAM-4, for instance, of 3.5 dB for a transceiver bandwidth of 17 GHz. However, PAM-8 and SPR-PAM-4 exhibit a much more stable performance than PAM-4. Moreover, FFE and DFE achieve a similar
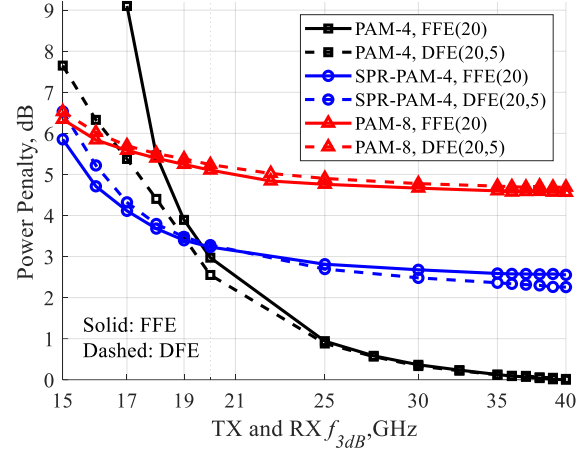
Fig. 3. Power penalty for different modulation formats as a function of transceiver 3-dB bandwidth for back-to-back 100 Gbps transmission [22]. BER target = 10^{-2}. Optical receiver: SOA+PIN. The zero-penalty corresponds to the PAM-4 unconstrained bandwidth case.

performance for these formats. This is because the PAM-8 symbol rate, and thus the signal bandwidth, is smaller (i.e. 33 GBd) than for PAM-4, and therefore, inside the 25G-class device bandwidth range, the use of DFE still does not make a difference. In the case of SPR-PAM-4, in the referred range, the symbol rate to available bandwidth ratio is close to the optimum for partial response operation, so that DFE is not needed. SPR-PAM-4 overcome PAM-8 in the full region. SPR-PAM-4 has a 1 dB performance variation in the 17 – 25 GHz range, having a maximum penalty of 2.3 dB with respect to PAM-4 using 50G-class. Then, for 100 Gbps PON operation using 25G-class devices, SPR-PAM-4 is a promising format. In contrast, the intrinsic poorer sensitivity of PAM-8 against the PAM-4 variants, make this option very challenging to achieve the required PON power budget.

Recent experimental results have shown feasible 100 Gbps operation of PAM-4 using 25G-class devices over 25 km [32]. To limit the dispersion penalty, O-band operation was selected. A power budget of 29.9 dB and 31.1 dB is achieved by using FFE with 135 taps and DFE with 135 feedforward taps and 30 decision feedback taps, respectively. A SOA+PIN receiver architecture is used. In [24], a power budget of 31.5 dB is reported using similar conditions as in [32], but using DFE with less taps (23 feedforward and 2 decision feedback taps), and considering a stronger LDPC FEC with pre-FEC BER target of 1.9 x 10^{-2}.

An alternative to overcome bandwidth limitations, avoiding the receiver noise enhancement issue, is pre-equalization. For instance, by using root-raised cosine pulse shaping and time-domain pre-equalization, a 100 Gbps transmission using PAM-4 and 10G-class devices (~7 GHz bandwidth) is shown in [36]. O-band operation over 22 km of SMF is set. More complex receiver DSP is used: constant modulus algorithm (CMA) in combination with Volterra Non-Linear Equalizer (VNLE).

E. Chromatic dispersion (CD) impact and DSP countermeasures

Chromatic dispersion, a linear distortion for the optical field, becomes a non-linear distortion when using direct detection due to the square-law of the photodiode. The related CD power penalty, similar to the penalty arising from bandwidth limitations, tends to have a steep transition from "low penalty" to "high penalty" zone (see, for instance, Fig. 4). For 10 Gbps un-equalized IM-DD systems, this transition occurs at about 50-km in C-band. Then, CD was of not a concern in PON up to XGS-PON for a target distance of 20 km. However, for 50 Gbps systems, the impact of CD becomes critical. According to measurements and simulations

presented in [33], to maintain the CD penalty below 1 dB using un-equalized OOK, a maximum accumulated dispersion ($D·L$, where L is the fiber length, and D is the CD coefficient) of ~50 ps/nm can be tolerated. In this conditions, 20 km C-band operation is completely unfeasible, and O-band operation is very restricted. For instance, considering a 20 km fiber length, the nominal O-band $|D·L|$ is 55 s/nm and the worst case $|D·L|$ is 77 ps/nm. Alternatives to increase the dispersion tolerance include using more CD resilient modulation formats (such as duobinary), DSP techniques (such as equalization), and chirping management [22], [33]. Although the phase information is lost in conventional IM-DD signals, CD penalties can be partially mitigated through the use of a FFE [37]. Due to noise enhancement of this kind of equalizers, the strong frequency notches to equalize, generated because of combination of dispersion and DD reception [38], set a limit to the amount of CD that can be compensated. Using single-side modulation (SSB), which frequency up-converts the signal and sends it alongside part of the optical carrier, the phase-information can be recovered using DD detection. Then, complete CD compensation can be performed. However, as stated in sub-section 3.H, the required PON sensitivity is difficult to achieve with SSB systems. Moreover, their analog-to-digital converter (ADC) and digital-to-analog converter (DAC) sampling rate should be high (typically 4 samples/symbol, which for a 50 GBd system means 200 GSamples/s) [39].

Regarding the use of more CD-resilient modulation formats in 50G-PON, un-equalized EDB can tolerate up to $D·L$ = 80 ps/nm with CD penalty <1.5 dB [33]. When combining EDB with FFE (20 taps), this format can tolerate up to 100 ps/nm with a CD penalty < 1 dB [15]. According to [33], OOK with FFE (5 taps) and DFE (1 tap) together, is able to achieve a $D·L$ = 80 ps/nm with a CD penalty of 1 dB. If the previous setup is further combined with chirp management, i. e. selecting an EML with proper chirp-factor of α=-0.5, the CD penalty in the range $D·L$ = 0 – 80 ps/nm can become negligible (<0.2 dB) [33]. Then, O-band operation, even in worst case scenario, becomes feasible for 50G-PON, thus defined as the optical band for both upstream and downstream operation for 25G- and 50G-PON, in contrast with all previous PON generations operating one direction in O-band and the other in S-, C- or L-band.

Moving to 100 Gbps and beyond will exacerbate the CD tolerance problem. Provided that the inherent back-to-back sensitivity reduction is somehow compensated, a jump from binary to higher order formats seems the only feasible solution to increase the tolerance to CD at higher than 50 Gbps rates. In Fig. 4, we show simulation results comparing the performance of PAM-4, SPR-PAM-4 and PAM-8 as a function of the accumulated link dispersion, for a chirp-less 100 Gbps transmission [22]. Fig. 4a and Fig. 4b assume 50G-class and 25G-class devices,
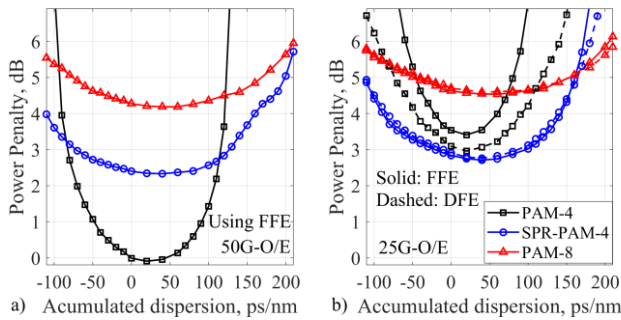
respectively (see sub-section 3.D). FFE is assumed in the curves of Fig. 4a. FFE and DFE curves are displayed in Fig. 4b. Note that the curves shown in Fig. 4 are asymmetric with respect to the zero-dispersion ($D·L$=0) point. This arises from the well-known relation between Kerr nonlinear induced self-phase modulation (SPM) and dispersion: SPM can partially compensate dispersion when D>0, whereas it worsen the CD impact when D<0 [22]. Then, a smaller penalty is obtained for the same absolute value of D if its sign is positive. Considering a 1-dB penalty as a reference for comparison, a $D·L$ in the range of -50 to 100 ps/nm can be tolerated by PAM-4 (aided by DFE if using 25G-class O/E), $D·L$ = -100 to 150 ps/nm by SPR-PAM-4 (FFE alone is enough), and $D·L$ = for -100 to 180 ps/nm by PAM-8 (FFE alone is enough). For 50G-PON, the maximum tolerated accumulated dispersion for downstream was defined equal to 77 ps/nm. Assuming a similar requirement, SPR-PAM-4 seems a feasible solution for 100 Gbps transmission in O-band. The performance of more dispersion resilient formats than PAM-4 and SPR-PAM-4, such as CAP and DMT [18], needs to be analyzed for 100 Gbps transmission in O-band. Although CAP and DMT require more complex transmitter and receiver DSP than PAM-4 or its partial response variant, it is worth to analyze their technical figures of merit under very high-speed conditions.

F. Challenges for DSP nonlinear distortion compensation

The optical fiber and the optoelectronic devices are sources of non-linear (NL) distortion. The very demanding conditions to achieve >50 Gbps, are pushing PON operation into NL regime, producing distortions that did not play a relevant role in previous PON generations. For instance, due to the need of higher launch power to achieve the required power budget for ultra-high capacity PON systems, fiber non-linearities, such as Kerr effect, introduce non-negligible power penalties. As an example, in a 100 Gbps PON operated in C-band using digital CD pre-compensation, and a launch power of +11 dBm, it has been estimated by simulations [40] and experiments [41], a ~2.5 dB penalty directly associated to fiber non-linearities. An example of NL distortions introduced by O/E devices is the non-linear current to optical power conversion that takes place in the optical modulator that has to be admitted to increase the optical modulation amplitude (OMA). This E/O NL conversion results in power penalties due to eye-distortion, particularly when moving from PAM-2 to PAM-4. A similar distortion is produced at the electrical amplifier because the NL input-output profile for large input signals. At the receiver side, an extra source of non-linearity derives from the combination of CD and square-law of the photodiode. In addition, the introduction of SOA as pre-amplifier, introduces NL distortion due to saturation gain and noise power-level dependency.

DSP techniques to counteract the effect if non-linearities, such as pre- and post- equalizers based on VNLE [42], neural networks (NN) [43] or NL Tomlinson-Harashima precoding (THP) [44], to mention some popular approaches, have been proposed. Simplified ad-hoc solutions to deal with NL distortion, such as polynomial functions [45] and look-up-tables [46] have been also analyzed.

Let us give some examples of direct-detection 100 Gbps PON experimental results from recent literature including NL compensation. In [43], a PAM-8 system with a high launch power up to 18 dBm, achieving a power budget of 30 dB at BER=10^{-2} was demonstrated. C-band operation over 20 km of fiber was shown, thus introducing strong NL distortion. The proposed solution was based on NN equalization, which was compared against VNLE. It was shown that the NN equalizer outperforms VNLE to deal with strong non-linearity. In [41], a simplified square-like function (SQRT) to deal with NL at receiver side is compared against VNLE for a PAM-4 system with 11 dBm of launch power. A power budget up to 34.7 dB and 33 dB is achieved for C-band 16 km operation using VNLE and SQRT, respectively (CD digital pre-

Fig. 4. Power penalty for different modulation formats as a function of accumulated dispersion for 100 Gbps transmission [22] assuming: a) 50G-class devices and b) 25G-class devices. BER target = 10^{-2}. Optical receiver: SOA+PIN. Same zero-penalty reference corresponding to the PAM-4 dispersion-free unconstrained bandwidth case.

compensation was applied). Using VNLE and SQRT was shown to achieve a gain of 3 dB and 1.3 dB against FFE/DFE, respectively. In [44], a PAM-4 system with a power budget of 34 dB in O-band is demonstrated using a DML with a launch power of 13 dBm. NL THP at transmitter and 2nd order VNLE at RX are used. In [47], a PAM-4 system with a power budget of 30 dB is shown, operated in O-band (20 km SMF). A recurrent NN based equalizer using parallelization is used at receiver side to deal with NL distortion. In [32], a power budget of 31.58 dB is achieved using PAM-4 with THP at transmitted and FFE at the receiver side. A launch power of 11.34 dBm is set. All of the previously described architectures employed SOA+PIN receiver.

G. Burst-mode receivers and DSP for upstream

Compared to all other optical fiber transmission, PON is burst-mode in the upstream, with very demanding characteristics [39]:
- 20 dB weak-strong optical power variation in worst-case
- Burst duration has large variations too, depending on traffic.

To deal with these challenges, the receiver optoelectronics should be developed ad-hoc to handle very fast automatic gain control circuits and phase/clock recovery [48], [49]. Moreover, moving to a DSP-based receiver exacerbates the technical hurdles. For instance, the large power variation should be leveled before analogue-to-digital conversion, otherwise, the soft bursts suffer from not fully using the vertical resolution of the ADC [39]. Another issue: traditional adaptive equalizer have an initial training phase for optimizing taps coefficients. Standard FFE training can use thousands of bits [33], [15], [48], which is too long for PON burst-mode operation. This is still an open research issue. In fact, the first generation of 50G-PON is actually at 25 Gbps in the upstream [33], so that strong and optimized equalization is not needed.

Several publications have studied adaptive equalizer variants suitable for the PON upstream. For instance, to shorten the time of equalizer convergence, an initial set of FFE taps values are evaluated during discovery phase for each ONU, stored in a memory after convergence and then charged to the FFE at the beginning of each burst [15], [50]. Other alternatives are based on the development of more complex adaptation algorithms able to converge faster than the typical Least-Mean Square (LMS) method. For instance, recursive least square (RLS) [51], [52] and gear-shifted LMS [48].

H. Single sideband solutions

While the mainstream standardization activities and the related researches on DD PON have focused on NRZ OOK and PAM-4 (also in their duobinary variants), some research level proposals have also addressed less common modulation formats based on single sideband (SSB) modulation, mostly to combat CD when the target is moving the transmission to C- or L- bands. For instance, in [53] and [54], the Authors showed the possibility to SSB transmission in C-band at 56 Gbit/s without significand CD penalty. Anyway, the achieved received optical power sensitivities tends to be quite far from those required to meet the PON typical specification (ODN loss above 29 dB), unless EDFAs are used at the receiver [55].

4. PON using coherent solutions

A. Motivation of introducing coherent systems

Up to now IM-DD systems have been preferred for PON due to their cost and simplicity as compared to current coherent systems. However, some trends show that IM-DD data rate capacity is reaching a ceiling at 100 Gbps [39], [56], [57]. Complex IM-DD systems, achieving more than 400 Gbps, have been reported [58], but exhibiting sensitivity values not suitable for PON. Moreover, jumping from 50 Gbps/λ to 100 Gbps/λ and beyond keeping the IM-DD approach is very challenging due to CD

penalty limitations, as discussed in sub-section 3.E. IM-DD 100 Gbps C-band operation has been shown in [43], but requiring a very high launch power of ~18 dBm and a complex RX DSP based on machine learning. By using RX DSP with similar complexity of current 50G-PON proposals, such as FFE or DFE, 100 Gbps C-band operation is practically impossible and O-band feasible operation is achieved with almost no margin for worst-case scenarios [22].

On the other hand, coherent systems are able to fulfill the PON power budget requirements for data rates beyond 100 Gbps [56], [57]. In [57], it is shown that 100 and 200 Gbps/λ are feasible from a power budget perspective, using single- or dual-polarization QPSK modulation, providing additional margins of >8 dB beyond the 29 dB power budget required by N1 class PON standards. However, to be applied to PON there are three major hurdles regarding coherent technology:
- Low target costs (even lower than data-center).
- Low power consumption (similar to data-center requirements).
- Burst mode operation in upstream (specific for PON).

Many research groups are today working on coherent PON in the following directions:
- Component integration process to reduce costs (like silicon photonics [59]).
- Simplified coherent receivers.
- New ASIC solutions to reduce power consumption [60].
- New DSP algorithms for burst-mode equalization and phase/clock recovery.

Discussions about fair comparison between coherent and DD solutions in terms of cost and power consumption have been presented in [57] and [61], respectively. Focus of this paper is the role of DSP algorithms as key enablers of simplified coherent alternatives. In sub-section 4.B we will briefly review some of the proposed architectures with reduced complexity than the full-coherent approach widely used in long-haul and metro applications. Then, in sub-section 4.C, we will focus on the DSP schemes specific for coherent PON applications, devoting sub-section 4.D to the specific issues related to burst-mode transmission in the upstream, and the main DSP solutions proposed so far.
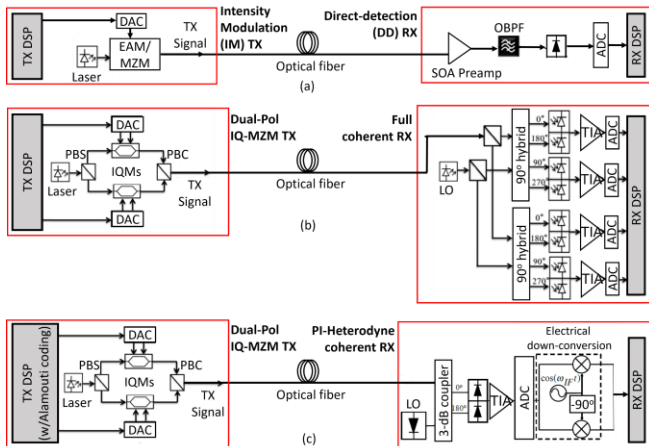
B. Full-coherent receiver and simplified coherent solutions

A full coherent system is shown in Fig. 5(b). A dual-polarization IQ-MZM is used at the transmitter in combination with a polarization- and phase-diversity intradyne coherent receiver, able to detect the amplitude, phase and polarization variations on the signal, thus enabling high-order modulation [62]. Other advantages of this scheme are the high-sensitivity it can achieve and its capability of correcting for device and channel distortions, such as CD, polarization mode dispersion and polarization rotations, by using DSP [63], [64]. However, as mentioned before, its complexity is considered too high for the PON realm, especially at the ONU side. For the sake of comparison, the simpler IM-DD system aided by DSP, currently proposed for 50G-PON implementations, is shown in Fig. 5(a).

To enable data rates beyond 50 Gbps, extra complexity should be added, preferably at the OLT side, which is a shared element. Intermediate approaches between IM-DD and a full-coherent system are the simplified coherent architectures that have been proposed recently. All of them sacrifice performance to reduce complexity in terms of decreasing the required number of optoelectronic components [65], and thus cost (assuming cost and complexity are linked). While some groups envisage that this sacrifice is not needed arguing that the full-coherent solution will eventually be cost-effective enough thanks to progress in photonics integrations, there are several groups proposing simplified approaches assuming this full-coherent cost reduction may not arrive on time.

The conventional full coherent receiver is formed by a local oscillator (LO), a polarization beam splitter (PBS), two 90° optical hybrids, 4 balance photodiodes (BPD), 4 transimpedance amplifiers (TIA) and 4-ADCs. An initial simplification consists on moving from the intradyne to the heterodyne reception, by including electrical down-conversion, which enables replacing the 90° optical hybrids by a 3-dB coupler and halving the number of BPDs, TIAs and ADCs [66]. This simplification comes at the cost of larger bandwidth requirements of the components (to allow the digital baseband conversion). A further simplification consists on receiving a single-polarization and removing the PBS from the receiver. Sacrificing the dual-polarization scheme halves the data rate system capacity. However, the PBS is an element difficult to integrate, and a single-polarization scheme allows reduction of the required number of elements to only one BPD, one TIA, and one ADC (see receiver of Fig. 5(c)). To avoid LO polarization alignement with the incoming signal, a polarization-insensitive approach should be use. Polarization control at the transmitter using polarization-time coding is a usual approach to obtain polarization-insensitive operation. Some of this coding techniques are Alamouti coding [66], polarization scrambling [67] or differential group delay (DGD) pre-distortion [68]. Performance comparisons of the aforementioned approaches using OOK [69] and QPSK [65] formats have been performed. It has been shown that the heterodyne polarization-insensitive coherent receiver in combination with Alamouti coding, shown in Fig. 5(c), achieves a good trade-off between simplicity and performance, outperforming the other single-polarization techniques. This approach requires, to perform polarization-time coding, a dual polarization IQ-MZM (thus keeping the same complexity as the full-coherent transmitter) to send redundant information in the X and Y polarizations. By means of the Alamouti equalizer, this redundancy is used at the receiver side to properly detect the signal irrespective of the random polarization states variations induced by the channel [70]. The required DSP used at receiver to enable this alternative is discussed in next sub-section.

In [71], a 100 Gbps/λ PON system using the Alamouti simplified coherent system is demonstrated, achieving C-band operation over 80 km of single-mode fiber (SMF), and an power budget of 36.6 dB at a BER target of 4 x 10^{-3}. Recently, 200 Gbps/λ PON operation has been demonstrated using the abovementioned system, reaching 25 km in C-band and a power budget of 32.8 dB at BER target = 10^{-2} [72].

Compared to a full coherent system, the Alamouti simplified coherent system requires four times more electrical system bandwidth to transmit the same bit rate. A factor of two spectral efficiency reduction is lost due to the use of single polarization, and the other factor of two comes from the heterodyne detection. This capacity reduction is the price to pay to achieve the considerable reduction in the number of components and in DSP complexity. Compared to a DD system, the extra elements of the referred heterodyne receiver are just a 3-dB coupler, the LO and one more photodiode. This extra complexity could be further reduced by using a single-ended photodiode approach. For instance, 100 Gbps feasible operation using a single-photodiode is shown in [72], achieving a power budget of 32 dB. Moreover, a common laser architecture can be used in the transceiver, thus not requiring an extra laser to act as LO, as shown in [73]. Then, in terms of optical complexity, the DD receiver does not hold big advantages. In contrast, the dual polarization IQ transmitter is more complex than an intensity modulator one. Anyway, considering the downstream operation, the simplified coherent architecture places this extra complexity at the OLT and not at the much more cost-sensitive ONU. Performance comparisons between the Alamouti simplified coherent system and IM-DD systems have been reported in [61], [74], [75], showing the clear advantages of simplified coherent against IM-DD in terms of achievable power budget and resilience to dispersion for high-capacity PON.

C. DSP for coherent solutions

One of the key concerns for downstream coherent receiver is the low complexity DSP design to reduce the power consumption of the ASIC. First, consider the standard dual-polarization intradyne receiver, in which the key DSP functionality blocks are: IQ imbalance compensation, equalization of static and dynamic channel impairments, timing recovery, frequency offset compensation, carrier phase recovery and FEC decoding [62]. Some alternatives to reduce DSP complexity are discussed in the following.
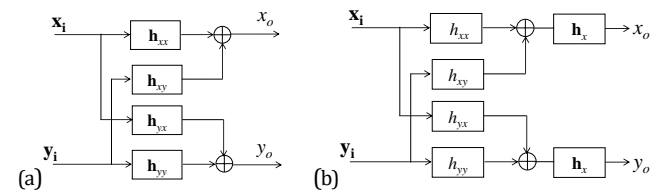
Adaptive Equalization:
Apart from the FEC, adaptive equalization is a major power consuming block [76]. Herein, we discuss three approaches to reduce the complexity of the adaptive equalizer.

1.   Multiplier-free update:
Conventionally, a 2x2 multiple-input multiple-output (MIMO) set of adaptive finite impulse response (FIR) filters are used for equalization and polarization demultiplexing, as shown in Fig. 6(a). The output samples of the filters are computed as:

$$x_o = \mathbf{h}_{xx}^{\mathrm{H}}\mathbf{x}_i + \mathbf{h}_{xy}^{\mathrm{H}}\mathbf{y}_i$$
$$y_o = \mathbf{h}_{yx}^{\mathrm{H}}\mathbf{x}_i + \mathbf{h}_{yy}^{\mathrm{H}}\mathbf{y}_i \qquad (1)$$

where, $\mathbf{h}_{xx}$, $\mathbf{h}_{xy}$, $\mathbf{h}_{yx}$, and $\mathbf{h}_{yy}$ are the column vector of length N representing the tap weights of FIR filters, $\mathbf{x}_i$ and $\mathbf{y}_i$ representing a sliding block of N input samples from x- and y- polarization, respectively and

Fig. 5. (a) DSP-aided IM-DD system; (b) Polarization- and phase-diversity intradyne "full" coherent system; (c) "Low-complexity" polarization-insensitive (PI) single polarization heterodyne coherent system using Alamouti coding and equalization. EAM: Electro-absorption modulator, MZM: Mach-Zehnder modulator, IQM: IQ-Modulator, LO: Local Oscillator, PBC: Polarization beam combiner.

Fig. 6. (a) Conventional 2x2 MIMO set of adaptive FIR filters; (b) Simplified single-tap 2x2 MIMO equalizer followed by a pair of adaptive FIR filters.

superscript $(.)^H$ denotes conjugate transpose. The filter tap weights are updated using any gradient descendent based algorithm such as CMA, radius-directed algorithm (RDA), or decision-directed LMS algorithm. For constant modulus modulation format like QPSK, CMA is well-suited for which the update equation can be written as:

$$\mathbf{h}_{xx} \leftarrow \mathbf{h}_{xx} + \mu e_x \mathbf{x}_i x_o^*$$
$$\mathbf{h}_{xy} \leftarrow \mathbf{h}_{xy} + \mu e_x \mathbf{x}_i y_o^*$$
$$\mathbf{h}_{yx} \leftarrow \mathbf{h}_{yx} + \mu e_y \mathbf{y}_i x_o^* \qquad (2)$$
$$\mathbf{h}_{yy} \leftarrow \mathbf{h}_{yy} + \mu e_y \mathbf{y}_i y_o^*$$

where, μ is the convergence parameter and the error terms are given as $e_x = 1 - |x_o|^2$ and $e_y = 1 - |y_o|^2$. If we consider the number of complex multiplications as the key computational cost, it is found from Eq. (1) that the filtering stage requires $4N$ complex multiplications for computation of each symbol. On the other hand, $4N$ complex multiplications required to multiply gradient vector with input vector are dominant complexity for filter tap weight updating, considering that the value of μ is a negative power of 2 (thus can be implemented by shift operation) and the error term is real valued. Thus, output calculation and filter updating approximately contribute equal complexity for the adaptive equalizer. Now, the filter updating can be made multiplier-free by using sign-sign CMA as described in [77], [78], thus halving the overall complexity. The update is done by keeping sign of the error term and the output sample, which is essentially using only the sign of the gradient, as follows:

$$\mathbf{h}_{xx} \leftarrow \mathbf{h}_{xx} + \mu \text{sgn}(e_x)\mathbf{x}_i \text{csgn}(x_o^*)$$
$$\mathbf{h}_{xy} \leftarrow \mathbf{h}_{xy} + \mu \text{sgn}(e_x)\mathbf{x}_i \text{csgn}(y_o^*)$$
$$\mathbf{h}_{yx} \leftarrow \mathbf{h}_{yx} + \mu \text{sgn}(e_y)\mathbf{y}_i \text{csgn}(x_o^*) \qquad (3)$$
$$\mathbf{h}_{yy} \leftarrow \mathbf{h}_{yy} + \mu \text{sgn}(e_y)\mathbf{y}_i \text{csgn}(y_o^*)$$

where sgn(.) is the signum function and csgn(.) is the complex signum function treating the signum function of real and imaginary part of the complex variable independently.

2. Separation of polarization-independent filtering:

To reduce the filtering complexity, one approach is to separate out the polarization demultiplexing function which can be realized with a single tap circuit. Thus, the adaptive equalizer is now composed of 1-tap 2x2 MIMO followed by two N-taps adaptive FIR for each polarization as shown in Fig. 6(b) [79]. Therefore, the number of long FIR filters is halved. Such simplification comes at the expense of sacrificing the capability of any polarization mode dispersion compensation; however, for the short reach access network very small penalty is expected for polarization mode dispersion. Some variants of the equalizer structure shown in Fig. 6(b) have also been investigated for further improvement of complexity/performance. For example, two polarization independent filters can be used first, followed by 1-tap 4x4 to reduce the number of multipliers for $T/2$-spaced input sequence [80]. The effectiveness of the structure to include the IQ skew compensation by replacing the N-tap complex-valued filters with the real-valued filters has also been studied in [81].

3. Frequency-domain equalization:

For the conventional time-domain equalization (TDE), the complexity of filtering and updating are $\mathcal{O}(N)$. However, for an adaptive frequency domain equalization (FDE), the complexity is $\mathcal{O}(log_2(N))$ and thus for a moderately large number of taps (N>8), it enables the reduction of complexity over TDE [82]. Moreover, a high degree of parallelism is required to implement the DSP in a field-programmable gate array (FPGA) or CMOS ASIC. Therefore, it is desirable to implement the
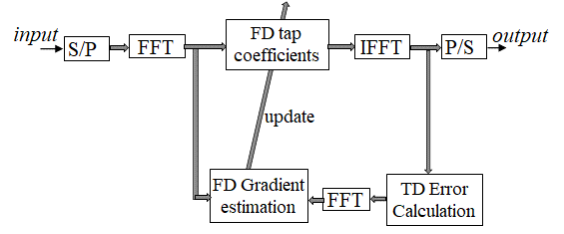

Fig. 7. Adaptive frequency domain equalizer (FDE) structure.

adaptive filters in block-by-block basis, rather than a sample-by-sample process and FDE is an efficient way to do so.

As shown in Fig. 7, in the adaptive FDE, after serial-to-parallel conversion, the input sequence is first converted in the frequency-domain using fast Fourier transform (FFT) and then filtering in done in frequency domain usually utilizing overlap and save method. The filtered signal is converted back in time domain using inverse FFT (IFFT) and error signal is calculated in the time-domain from a block of outputs. Then the error signal is transformed back in frequency domain to calculate the gradient. With the estimated gradient, finally the filter taps are updated in frequency domain using the gradient decent algorithm.

When using QPSK format, the sign-sign multiplier free time domain update along with frequency-domain filtering, enabling a hybrid time-frequency domain equalization, can also be used for further reduction of complexity even over the adaptive FDE based approach [83].

Carrier phase recovery:

Low complexity carrier phase recovery is another important task in coherent downstream receiver. In conventional carrier recovery, phase estimation is done over two polarization tributaries independently. In [79], the complexity of carrier recovery was reduced by estimating the phase noise in one polarization only, say for x-polarization. Then the phase noise in the y-polarization is estimated as the same as x-polarization plus the offset between two polarizations. Reduced complexity multiplier-free carrier phase estimation has also been investigated for coherent systems [84] .

Equalizer for Alamouti-coded simplified receiver:

Due to special coded signal in two polarizations, the conventional 2x2 MIMO equalizer is not suited to Alamouti-coded signal used for a simplified receiver. Usually, the received symbols are split into even and odd sequences and even sequences are conjugated before filtering in the 2x2 MIMO equalizer as shown in Fig. 8(a). After equalization, the carrier phase is estimated, for example using one-tap decision-directed LMS based estimation which is feedbacked in the equalizer to correct the phase rotation. The details of the update equations can be found in [70].
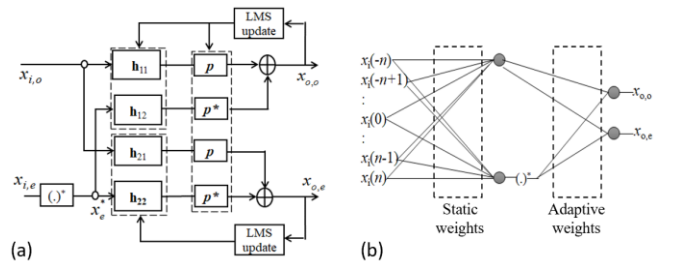

Fig. 8. DSP circuits for: (a) Alamouti joint equalization, polarization tracking and carrier phase recovery [70], (b) Alamouti equalizer realisation using NN with linear activation function [85].

The Alamouti equalizer in Fig. 8(a) can also be realized with an artificial neural network (ANN) with linear activation function [85]. The complex-valued ANN only contain two layers each having two linear neurons as shown in Fig. 8(b). The first layer can be considered as static equalizer compensating CD and impairments due to bandwidth limitations and need to be trained once at the startup. One of the neurons' outputs is conjugated before feeding to second layers. Weights of the second layer are updated periodically for adaptive polarization tracking. Two outputs of the ANN are the estimated QAM signal-pair as a complex number.

D. Challenges for DSP in coherent burst-mode receivers

As mentioned in sub-section 3.G, the burst-mode operation, particular for TDM-PON, pose specific challenges when using DSP algorithms, related with the variable burst duration and the fast convergence of the equalizers. In coherent systems, a wide dynamic range severely degrades the signal-to-noise ratio of the received signal due to two factors. Firstly, if the gain of linear TIA used in the coherent receiver is optimized for the weak burst signal, the strong bursts are clipped due to the saturation of TIA degrading its performance. Secondly, if the ADC's full-scale range is adjusted to detect strong bursts, the weak burst does not use the full vertical resolution and suffers from large quantization noise. To cope with the wide dynamic range, several approaches have been investigated. One of the methods is to use either burst mode TIA [86] or burst mode optical amplifier like burst mode EDFA or burst mode SOA [87], [50]. Combination of using both burst-mode SOA and burst-mode TIA enhance the tolerable dynamic range [88]. A second approach, only suitable for coherent systems, is to control the LO power: a large LO power for the weak burst and a small LO power for the strong burst in such a way that the detected signal at photodiodes is same irrespective of incoming signal power [89]. Another straightforward approach is ONU power levelling method [90] where transmit power of each ONU is based on the distance (and thus loss) to the OLT, in order the bursts have almost the same power level when reaching the OLT.

Regarding the fast convergence adaptive equalization within short preamble time of a burst several methods have been investigated. For example, in [50], storing the equalizer tap values after convergence using CMA algorithm during the discovery process was used to set the initial coefficients for next bursts arriving from the same ONU for a faster convergence time.

Another important issue for high-speed coherent upstream is the efficient design of preamble with corresponding burst-mode DSP. As an example, [91], a short preamble of 71.68 ns with three sync patterns was demonstrated for a 100G coherent upstream. The first sync pattern was used for burst-clock recovery, especially designed second sync pattern performed multiple DSP functionalities, including frame synchronization, state-of-polarization estimation, and frequency offset estimation and finally a third sync pattern is used for channel estimation based on CMA algorithm.

Note that the complexity of the coherent receiver for the upstream is usually not as much concern as the ONU receiver since the cost of OLT equipment is shared among many users. Therefore, to get better performance, a full dual-polarization coherent receiver can be considered at the OLT side while a DML or EML-based simple transmitter can be used at the cost-sensitive ONU side [92]. Still, the OLT coherent receiver should work in burst-mode, a request that opens several technical challenges, as discussed before and described in detail in [93], such as dynamic range adaptation to allow a linear handling of the received signal, and then fast and DSP-based polarization, frequency, phase and clock recovery. Though these challenges have not yet been implemented in a commercial product, a vast literature already exists in the area of burst-mode coherent, not only in the area of low-

complexity upstream PON [94], but also in previous works on all-optical packet switching, such as in [95].

5. Conclusions

We review in this paper the evolution of PON standardization and research proposals to find physical layer solutions enabling 50, 100 and 200 Gbps/λ, focusing on the available DSP solutions to achieve these targets.

While the IEEE and ITU-T Recommendations for up to 50 Gbps/λ have already been released, evolutions towards 100 and 200 Gbps/λ have yet to be defined. The final decisions between sticking with direct detection solutions or ultimately moving to coherent detection will depend on a mix between:

- Techno-economic evolution of coherent technologies in other fields, in particular on the intra- and inter-datacenter applications
- Actual timeline of market requirements of 100+ Gbps in PON

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