Coherent Access: A Review

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Abstract—**In this paper, we will address the benefits of the coherent detection in future optical access networks. The scarcity of the optical spectrum, the required flexibility, and constant evolution of requirements highlight the effectiveness of coherent techniques toward the future passive optical networks (PON). A set of architectures for coherent optical access networks will be presented and the key attributes of each scenario will be investigated. In addition, as a basis to decrease the cost of the local oscillator (LO) at customer side, we experimentally investigate the possibility of using a low-cost laser as LO with real-time detection of a Nyquist-shaped differential quadrature phase-shift keying (DQPSK) signal using simple 8-bit digital signal processing (DSP) on a field-programmable gate array. Moreover, we experimentally derive a set of optimized parameters and their impact on the network operation for coherent ultradense wavelength-division multiplexing (UDWDM) systems. The balance between the number of channels, power budget, and dynamic power range will be evaluated. Furthermore, we demonstrate a reconfigurable real-time receiver DSP for future flexible UDWDM-PON systems applying the DQPSK and D8PSK modulation formats. By reviewing some of the motivations for this technology, such as flexibility, spectral efficiency, as well as compatibility with software-defined networking, we show that this technology is approaching the required maturity.**

Index Terms—**Access networks, digital signal processing, Nyquist pulse shaping, optical coherent detection, passive optical networks, UDWDM.**

I. Introduction

FUTURE optical access networks (F-OANs) will have to take full advantage of recent evolutions in the field of optics. Although cost and data rate will remain as the major drivers, sustainability and flexibility also have to be included as enablers for the coming challenges of operators in the field.

During the last two decades, standards for optical access have evolved greatly and rapidly, with the two major groups, IEEE 802.3 and ITU-T [1], [2], playing an active role in the process. The first PON standards (broadband passive optical network (BPON), Gigabit passive optical network (GPON) and Ethernet PON (EPON)) relied on very basic and relaxed specifications on the components, where the upstream (US) and downstream (DS) signals were allocated bands greater than 10 nm, in order to keep laser and filter tolerances high and relax production costs and yields. Five years ago, these tolerances were tightened, in 10 Gbit/s Ethernet PON (10GE-PON) and 10-Gigabit-capable PON (XG-PON), showing that the industry and the standards have understood the evolution that the components and production cycles have gone through.

Recently, a great paradigm shift was included in the next generation PON2 (NG-PON2) standards [3]; dense wavelength division multiplexing (DWDM) has appeared to be the evolution path for a balanced cost and performance flexibility path. In this sense, tight filtering (100 GHz) and laser control $\pm$ 20 GHz) were introduced as two key passive/active technologies to reduce the total cost of network while keeping the performance. However, due to the versatility of end user types and highly time-varying traffic demands of mobile backhaul networks, the design of F-OANs ought to shift from traditional static to more dynamic and flexible. In addition, increasing network capacity ought to be gradual enough to facilitate the use of legacy network infrastructure to the highest degree possible and thus assure economically feasible network growth [4], [5]. Following this line, the F-OANs may include other degrees of flexibility and at that point, the coherent solution may be the next step. In Fig. 1 we present a spectral allocation of a network where several systems coexist in an optical distribution network (ODN). The spectrum scarcity is also a reality which needs attention in F-OANs, since most of the low loss bands of the fiber are fully exploited. Coherent technology, due to its inherent optical filtering properties, in conjunction with tunable laser sources, can help greatly in addressing this issue in a flexible and smooth way. The flexibility can be defined in terms of data rate with different modulation formats or symbol rate operation, as well as wavelength grid, network reach and the range of user requirements [6], [7]. For long reach PONs, different types of end users with heterogeneous bandwidth consuming Internet services and adaptive distance can be connected directly using a single fiber link. Therefore, besides flexible wavelength grids and data rate, dynamic power range characterization induced by different

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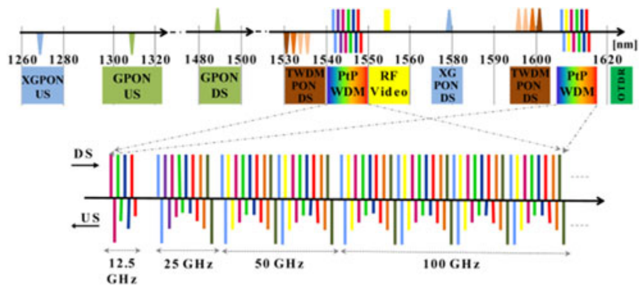

Fig. 1. Wavelength plan representation for multiple system configuration of F-OANs. The inset shows a flexible wavelength grid of UDWDM-PON system supporting a bidirectional transmission with unbalanced optical power per US channels.

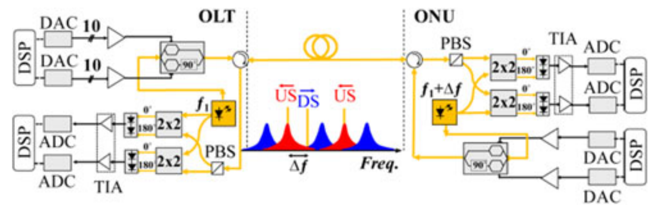

Fig. 2. Schematic diagrams of a simple coherent PON system based on high bandwidth DAC/ADCs at the OLT using a single laser and modulator for 10 UDWDM channels. The ONU side is based on coherent heterodyne detection using a polarization diversity receiver. ONU—optical network unit, OLT—optical line terminal, DAC/ADC—digital-to-analog and the analog-to-digital converter, DSP—digital signal processing, PBS—polarization beam splitter; LPF—low-pass filter, TIA—transimpedance amplifier.

distances from the optical network unit (ONU) to the optical line terminal (OLT) is an important factor.

To date, PON standards have been supported by intensity modulation of light. In the solutions for short reach, a lot of effort has been put nowadays in multi-level modulation, such as 4-ary pulse-amplitude modulation (PAM-4), in order to increase the data rate using minimum requirements for electrical analog bandwidth [8]. Following the latter idea, it is relevant to consider the benefits of combining the optical amplitude, phase and polarization to encode information, allowing a great increase in the data rate without putting too much pressure on the electrical side, and potentially keeping the components at a minimal cost. To meet these requirements, coherent detection is the technology of choice. However, the coherent solution for access is typically expensive because it requires complex control of the lasers due to the low symbol rate operation. Nevertheless, since the data rates in PONs are reaching the level of the initial Metro solutions, i.e. around 10 Gb/s [9], the laser linewidth requirements are expected to drop. Also, the coherent solution combined with advanced modulation formats requires advanced digital signal processing (DSP), which will also enable an increase in the flexibility of the system [7], [10]. The DSP is based on computational resources, by means of application-specific integrated circuits (ASICs) or field-programmable gate arrays (FPGAs), for instance. Nevertheless, currently the major difficulty in the DSP approach are the digital-to-analog and the analog-to-digital converters (DAC/ADCs), which are still a bottleneck for sampling rates above 1 GSa/s [11], [12].

A short overview of the coherent access systems has been presented in [13]. In this paper, we review the recent progress in coherent detection in OANs considering the state-of-the-art of the architectures. We address the benefits of each architecture considering the cost, flexibility, spectral efficiency and performance, supporting our conclusions with experimental data. We experimentally characterize a coherent ultra DWDM (UDWDM) PON system based on Nyquist-shaped differential quadrature phase-shift keying (DQPSK) signals over 80 km of standard single-mode fiber (SSMF) using a blind real-time DSP in the receiver supported by a commercial FPGA processing 2.5 GSa/s. The possibility of using a low-cost distributed feedback laser (DFB) as local oscillator (LO) is evaluated. Optimized power budget depending on the number of channels per flexible grid is investigated. In addition, the maximum power imbalance between adjacent channels at the input of the fiber is characterized. We also demonstrate a reconfigurable real-time receiver DSP for future flexible heterogeneous UDWDM systems using DQPSK and differential 8PSK (D8PSK) modulation formats. The combination of DSP, Nyquist pulse shaping and coherent detection is addressed as key enablers for F-OANs. These techniques guarantee seamless coexistence with legacy technologies.

The paper is organized as follows. Section II presents the coherent detection architectures for current and F-OANs. The experimental setup for evaluating the performance of the coherent UDWDM-PON technology is presented in Section III. The experimental results considering a flexible high capacity coherent system are discussed in detail in Section IV, including the assessment of the power budget, dynamic power range, spectral efficiency and flexible modulation formats. The summary of the paper and concluding remarks are discussed in Section V.

II. Coherent Access Architectures

The advantages provided by coherent reception for F-OAN have been widely reported by several research groups [14]–[45]. Due to its good ability to improve the receiver sensitivity and wavelength selectivity, an ODN power budget higher than 46 dB was obtained, together with an improvement in the number of the end-users in the system with dedicated WDM channels and data rates from 150 Mbit/s to 10 Gb/s and with a reach up to 100 km [15]. Transmission capabilities of this coherent real-time UDWDM-PON over deployed fibers were performed in two test beds (Berlin and Darmstadt, Germany) as reported in [16]. Fig. 2 shows the overall schematic diagram of this system. At the OLT, the transceiver for 10 users is aggregated in one DAC using the same modulator and tunable laser. The ONU consists of a tunable laser, an IQ modulator and a polarization diversity receiver, which were interfaced to the FPGA using two DACs and two ADCs. The tunable lasers in the OLT and ONU are used for the light sources in DS/US directions as well as for LO of coherent detections. The reception parts of both OLT and ONU are based on a heterodyne configuration using ADCs and DSP, where each ADC is used for one polarization and the separation of the I- and Q- components is performed in the DSP. The reception at the OLT was designed based on high bandwidth ADCs to support 10 users using a polymer wideband polarization diverse coherent receiver [15]. The reception at the OLT was designed based on high bandwidth ADCs to support 10 users using a polymer wideband polarization diverse coherent receiver [15].

In order to decrease the cost of highly aggregated coherent PON systems, the high analog bandwidth front-end for the generation and detection with a single laser can be replaced with several lasers integrated in the same wafer with the same number of modulators and receivers, and lower analog bandwidth DAC/ADCs. In addition, using an efficient pulse shaping

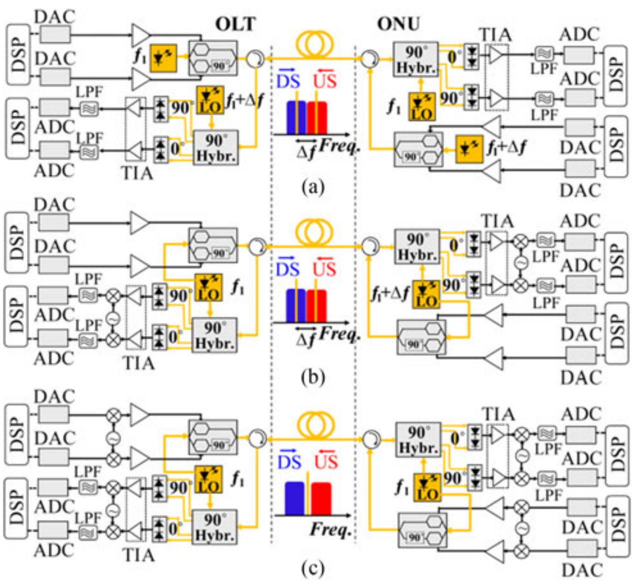

Fig. 3. Schematic diagrams of coherent PON system based on low bandwidth DAC/ADCs at the OLT and ONU (a) using two different lasers for the transmitter and receiver, or (b) using heterodyne detection with only a laser for the transmitter and receiver, or finally (c) using a heterodyne generation and detection approach with only a laser for the transmitter and receiver. In (b) and (c), the conversion to baseband can be carried out by RF devices such as mixers and analog filters, or in the digital domain after higher bandwidth ADCs without the need for RF devices.

technique, the required bandwidth for both transmitter and receiver can be also decreased. Fig. 3 presents three architectures to implement such a high aggregated coherent solution. For instance, in Fig. 3(a), using Nyquist pulse shaping the US signal is transmitted in the opposite direction to the DS signal, separated by a narrow frequency guard interval employing two different lasers for the transmitters and for the LO. Nyquist pulse shaping mitigates the linear crosstalk between US and DS channels caused by Rayleigh back-scattering (RBS) and also improves the mitigation of crosstalk and nonlinear impairments such as cross-phase modulation (XPM) and four-wave mixing (FWM) [17], [18]. In Fig. 3(b) the laser for LO and transmitter are the same. Therefore, the detection should be designed in heterodyne mode that results on using analog radio-frequency (RF) mixers and electrical filters in order to convert the signal to baseband before the sampling process, allowing to use low bandwidth ADCs. Furthermore, with Nyquist pulse shaping, single side band modulation can be easily implemented using frequency up/down-shifting from optical carrier of both US and DS directions [19], [20], resulting in full bandwidth allocation and matching wavelengths for the OLT and ONU link. We note that using higher bandwidth ADCs in the schematics of Fig. 3(b) and (c) there is no need for RF circuit devices that result in more flexibility in the price of more expensive digital device at client side. However, Nyquist pulse shaping brings extra complexity for the OLT and ONU transmitters, due to the required number of filter taps to apply the signal shaping, and also for the receiver, since for small raised-cosine (RC) roll-off factors (quasi-Nyquist signals) the recovery of the optimal sampling instant of the ADCs is more challenging [21]–23]. Table I reports an example of the DSP hardware requirements for a simple UDWDM-PON system demonstrated in [19] for single polarization DQPSK signals at 2.5 Gb/s using Nyquist pulse shaping and intradyne coherent detection. As observed, the Nyquist shaping

TABLE I
EXAMPLE OF THE DSP HARDWARE REQUIREMENTS IN TERMS OF REAL ADDERS AND MULTIPLIERS FOR AN UDWDM-PON SYSTEM USING NYQUIST PULSE SHAPING AND INTRADYNE COHERENT DETECTION FOR SINGLE POLARIZATION DQPSK SIGNALS AT 2.5 GBIT/S (N = DEGREE OF PARALLELIZATION = 16)

Algorithm	Multipliers		Adders		%
	–	N = 8	–	N = 8	
Nyquist Shaped (N_T = 32 taps)	–	–	8 N (N_T −1)	1984	35,7
Nyquist Emphasis (N_T = 3 taps)	4 N N_T	96	4 N (N_T −1)	64	15
Normalization	4 N + 4	36	5	5	5,3
Clock Recovery	16 N + 5	133	12 N + 8	104	22,4
	9	9	9	9	
Frequency Recovery	6 N	48	14 N − 1	111	8,9
Phase recovery	9 N	72	17 N − 1	135	12,8

The percentage column is estimated considering that a real adder is bit-width less complex than a real multiplier.

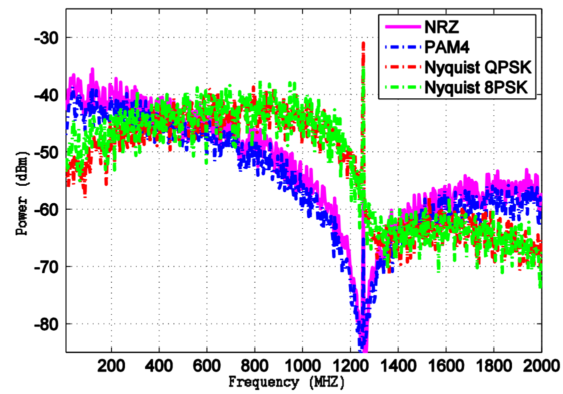

Fig. 4. Measured PSD of 1.25 Gbaud NRZ, PAM-4, DQPSK and D8PSK signals (with equal optical power) obtained by direct detection with a pseudo-random binary sequence (PRBS) of $2^{12}-1$. The resolution bandwidth and video bandwidth of electrical spectrum analyzer have been set to 30 kHz and 10 kHz, respectively.

is the critical subsystem in the transmitter DSP. Additionally, the peak-to-average power ratio (PAPR) of the signal increases when the roll-off factor (Nyquist signals) tends to zero, forcing the selection of DAC/ADCs with higher effective number of bits (ENOB).

As mentioned before, using the phase of the signal by employing advanced modulation formats such as DQPSK and D8PSK the spectral efficiency is increased. On the other hand, video overlay (analog or digital) broadcasts a series of electrically modulated subcarriers in the RF spectrum (from 55 MHz to 1 GHz) at C-band (1550–1560 nm) to each customer. It has been shown that in the coexistence scenario of PON technologies with RF-video overlay, mostly the 50–300 MHz region of RF-video signal is degraded due to the RF Raman crosstalk [46]—[48]. It also has been shown that the relative intensity noise induced by nonlinear Raman crosstalk in the video signal is strongly related to the power spectral density (PSD) of the digital modulation signals, demonstrating that reduced PSD in the frequency region of 50–300 MHz leads to lower impact of signal stimulated Raman scattering (SRS) on video overlay [46], [49]. The PSD of digital signal based on phase modulation obtained by a direct detection receiver has lower power in the lower frequency range. This behavior is also maintained using Nyquist pulse shaping applied to phase modulated signals. Fig. 4 depicts the PSD of the non-return-to-zero (NRZ), PAM-4, DQPSK and D8PSK signals with the same symbol rate. As shown in this figure, the PSD of Nyquist DQPSK and D8PSK is less than 10 dB compared to amplitude modulation signals. Therefore, Nyquist shaped phase modulation allows increased SRS tolerance compared to amplitude modulation. Therefore, apart from improved spectral efficiency, coherent PON system based on Nyquist shaped phase modulation may allow the aggregation of higher number of users coexisting with video overlay systems.

We note that the architectures considered in Fig. 3 are based on single polarization transmission/reception. The issue of polarization-dependency in these structures can be solved using several well-known techniques for automatic polarization alignment [50], [51]. Polarization tracking, as proposed in the seminal work of [50], can be achieved in single-polarization coherent receivers by monitoring the electrical voltage arriving at the ADCs, which are typically preceded by an analog low-pass filter to select the received channel. Alternatively, other options can also be considered, such as the polarization switching technique originally proposed in [51], which requires additional polarization scramblers at the transmitter sides and imposes up to 3 dB performance penalty. Nevertheless, it is worth mentioning that the architectures depicted in Fig. 3 can also be extended to support dual polarization transmission/ detection, thereby enabling polarization demultiplexing to be fully performed in the digital domain [10]. However, this approach was not pursued here in spite of offering doubled spectral efficiency, since it would also double the number of modulators, receiver photodiodes, TIA electrical amplifiers, DAC/ADCs, etc. There are several research works on optimization and characterization of coherent UDWDM based on dual polarization modulation that can be found in [24]–[26].

With the increasing demand on receiver DSP to tackle transmission impairments in optical access, alternatives have been sought to reduce the required processing for optical access. In particular, efforts have been made to allow the use of potentially low-cost wide-linewidth lasers as LO in coherent receivers [27] or even eliminate the need for a dedicated LO [28], provide tolerance to fiber nonlinearities, and insensitivity to the polarization state of the received signals [29], [30].

In this context, self-homodyne detection (SHD) has been recently proposed as a means to enable these features, at the cost of a reduced SE. SHD transmission is based on transmitting downstream the modulated signal polarization multiplexed with an unmodulated pilot tone (PT) originating from the same laser source, using a polarization beam combiner (PBC). A standard SHD-based PON scheme is presented in Fig. 5(a). At the ONU side, the PT is demultiplexed using a polarization beam splitter (PBS) and used as LO for coherent homodyne detection of the signal. This avoids both the need for a laser at the receiver to be used as LO and carrier frequency offset compensation mechanisms in the DSP. Also, since both signal and PT share a common laser source, the phase noise from the signal may be nearly cancelled by the matching phase noise of the PT. Moreover, the PT may be reused at the ONU for upstream transmission (or introducing the reflective concept based on reflective semiconductor optical amplifiers (RSOA), as presented in Fig. 5(b) and demonstrated in [31]), completely eliminating the need for lasers at the ONU.

Despite its advantages, SHD has significant drawbacks. Due to the transmission of the PT, SHD transmission allows only half the spectral efficiency of an equivalent polarization-multiplexed

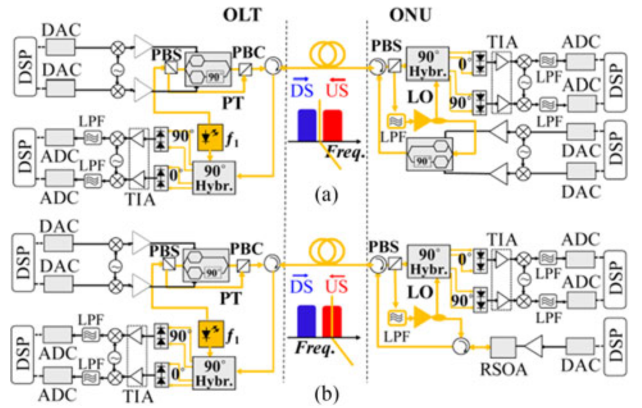

Fig. 5. Schematic diagrams of SHD-based (a) standard, and (b) reflective PON. Both of the schematic are based on heterodyne detection and the conversion to baseband can be carried out by RF devices such as mixers and analog filters, or in the digital domain after higher bandwidth ADCs without the need for RF devices. PBC—polarization beam combiner.

system, which translates into the need to use higher symbol rates or higher order modulation formats, to achieve equivalent capacity. Furthermore, the degradation of the PT along the transmission path by amplified spontaneous emission (ASE) will translate into a performance penalty, as shown in [32]. This is particularly significant for ASE-limited transmission systems, which is not necessarily the case with optical access networks, and leads to the need to use tight optical filtering at the SHD receiver. For shot-noise limited systems, SHD has the disadvantage of a limited coherent gain, dependent on the ratio between the signal and PT powers [32]. Similarly, in the case of UDWDM systems, SHD receivers cannot rely on heterodyne demultiplexing using a LO and therefore need to include optical filtering. Finally, the demultiplexing of the signal and PT requires the use of a PBS. As such, an optical polarization alignment mechanism such as digital self-homodyne detection (DSHD) [33] or polarization- independent (PI) SHD [30] is required at the receiver, in order to align the signal and PT polarization axis with those of the PBS. The cost of such mechanisms may be prohibitive for use in optical access networks.

In order to simplify the coherent transceiver architectures for both OLT and ONU using PI receivers, several works have been reported in [34]–[39]. As shown in [34] by means of extensive numerical simulations, a polarization-diversity detector scheme for a broadcast network based on 2×1 multiple-input–multiple-output (MIMO) orthogonal frequency-division multiplexing OFDM system has been investigated theoretically. In [35] a simple polarization-insensitive coherent receiver which consists of only a 3 dB coupler and a single balanced photodiode is experimentally demonstrated for transmission of 10.7 Gb/s Alamouti-coded OFDM signal. The proposed receiver does not consist any PBS or 90° optical hybrids and is implemented using a DSP which utilizes a polarization time block coding scheme combined with heterodyne detection.

In addition, projects like COCONUT [36]–[39] have suggested novel transmission strategies involving the combination of amplitude shift keyed (ASK) modulation with simplified coherent detection schemes based on analogue signal processing, as shown in Fig. 6(a). The configuration of the scheme is based on a 3×3 coupler followed by three photo-detectors in a coherent receiver, i.e. able to detect the phase of the signal. Since the

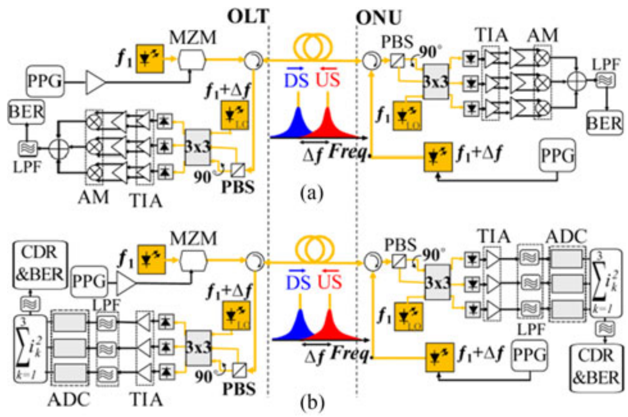

Fig. 6. Schematic diagrams of (a) the real-time analogue PI phase-diversity receiver for 1.25 Gb/s ASK signal without ADC/DSP [37], (b) PI phase diversity receiver architecture for offline transmission of 10 Gb/s ASK using simple DSP [39]. MZM—Mach-Zehnder modulator, AM—analogue multipliers, LPF—low-pass Bessel filter.

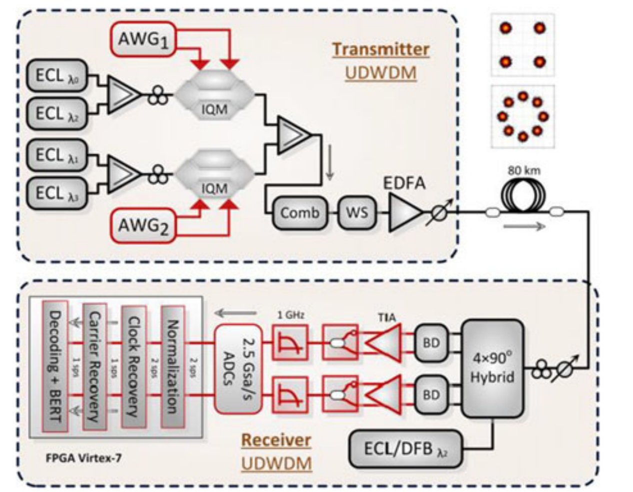

Fig. 7. Experimental setup with a UDWDM-PON system based on single polarization Nyquist shaped DQPSK and D8PSK signals over 80-km of a SSMF. AWG—arbitrary waveform generator, ECL—external cavity laser, IQM-IQ modulator, WS—wavelength selective switch (WS), EDFA—erbium doped fiber amplifier, DFB—distributed feedback laser, BD—balanced photo-diode.

application of this strategy is only for amplitude modulations, the electrical detection is basically based on the power detection of the signal as $\sum_{k=1}^{3} i_k^2$ in order to overcome the phase difference between the transmitter and the LO laser that was also detected. PI receiver of this schematic based on intradyne operation was achieved by only adding a PBS before 3×3 coupler and inserting an additional lightwave at the 3rd input of the coupler [37], [38]. The theoretical description of this PI receiver based on ASK modulation has extensively investigated in [38]. The real-time demonstration of PI coherent system using single channel 1.25 Gb/s NRZ is presented in Fig. 6(a). To make the coherent detection PI, the detection should be intradyne, which implies the use of two separate lasers, for LO and US transmission. This setup is based on rectangular NRZ pulse, and so the spectral efficiency is inferior compared to that of Nyquist pulse shaping. Recently, higher data rate NRZ transmission (up to 10 Gb/s (see Fig. 6(b)) and flexible data rate based on DPSK, QPSK and 8PSK signals were demonstrated in offline operation [39], [40]. These works exploit the unique feature of filtering and high sensitivity of low cost coherent optical access networks, resulting in field-trial demonstration [41].

III. Experimental Characterization

The experimental setup depicted in Fig. 7 is used to study the performance and characterization of a real-time coherent UDWDM-PON system employing single polarization DQPSK and D8PSK modulation formats. This proof-of-concept experiment is based on Fig. 3(a) by using separate lasers for the DS and US directions and only a single polarization state acquired from a commercial phase and polarization diversity coherent receiver. At the transmitter, two arbitrary waveform generators (AWGs) produce 1.25 Gbaud electrical signals. The offline DSP includes a DQPSK/D8PSK generator with a pseudo-random binary sequence (PRBS) of 2^{12}-1, followed by a RC shaping with 0.1 roll-off factor applied using 32-tap finite impulse response (FIR) filters. Compared to a root-raised-cosine (RRC), the RC shaping has the advantage of keeping the complexity of the system only at the transmitter side, simplifying the ONU DSP since no matched filter is required at the receiver. Furthermore, by using a simple RC shaping generation at the transmitter, the design of the filter can be based on a multiplier-free scheme [22]. In order to emulate the UDWDM grid, four optical carriers based on external cavity lasers (ECLs) (<100 kHz–linewidth) with a frequency separation of 2.5 or 3.125 GHz are injected into two IQ modulators (IQMs) driven by the electrical signal from the AWGs. The channels with even number have been created with the first modulator and odd number with the second modulator to make the adjacent channels uncorrelated. After a 3-dB coupler, the four modulated channels pass through an optical signal comb generator based on a Mach-Zehnder modulator (MZM) in order to replicate the 4 channels in 2 and 4 times in order to generate a UDWDM grid with 8 and 16 channels spaced by 2.5 or 3.125 GHz. At the output of the comb, the band of interest is filtered by one wavelength selective switch (WS), and the input optical power is set by an Erbium doped fiber amplifier (EDFA) and a variable optical attenuator (VOA).

This optical signal is then transmitted over 80 km of SSMF and at the receiver side, a VOA sets the received power. The channels are coherently detected using a 4×90^{o} optical hybrid with an ECL (<100 kHz–linewidth) or a DFB laser (<20 MHz–linewidth) LO set to the center channel λ_2 (intradyne detection). The optical channels are converted to the electrical domain using two balanced detectors (BD) and amplified by a transimpedance amplifier (TIA). Then, in order to achieve single-ended-to-differential conversion, a wide band balun board (ADC-WB-BB with 3 GHz bandwidth) is used and the output signal is then filtered by a 1 GHz low-pass filter in order to select only the center channel. Finally, the signal is sampled by two 8-bit 2.5 GSa/s ADCs and then recovered using DSP in a Virtex-7 FPGA. The DSP operates at 156.25 MHz with a degree of parallelization of 16 in order to process a sampling rate of 2.5 GSa/s. At the real-time DSP, the amplitude normalization is applied based on feedback control in order to improve the dynamic range of the DSP and then, the ideal sampling instant of the ADCs is compensated by a clock recovery algorithm using cubic interpolation based on 4-taps FIR filters with an 8-bit design, supported by feedback timing error estimation based on the Gardner power formulation. The carrier recovery is carried out by the Mth-power technique proposed in [52]: (1) for frequency recovery,

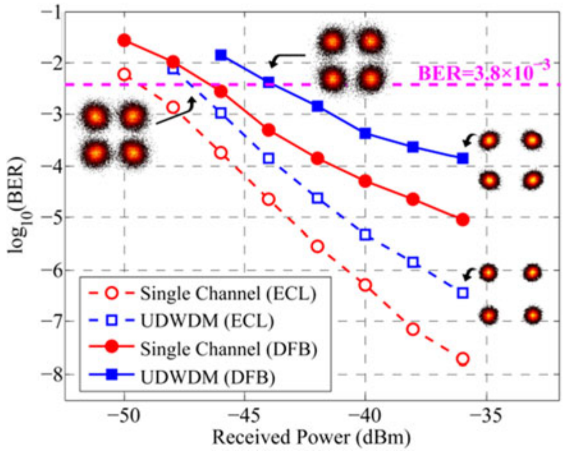

Fig. 8. BER performance versus received optical power of single- and multi-channel DQPSK signals considering an ECL and a DFB laser as LO and 2.5 GHz channel spacing.

it is used the differential phase-based method with a feedback flow and (2) for phase recovery, the Viterbi & Viterbi algorithm by feedforward averaged over 8 symbols, both implemented using only 8-bit resolution. Details of the DSP can be found in [22], [52]. No adaptive equalizer is used in the DSP, since the system is single polarization and no significant chromatic dispersion affects the signal due to the low symbol rate operation traditionally used in UDWDM-PON. After differential symbol decoding, which is use to overcome the cycle-slip (CS) that can be induced by the blind phase recovery algorithm [53], the bit error rate (BER) is estimated in real-time by bit error counting.

IV. Results and Discussion

Fig. 8 depicts the receiver sensitivity for DQPSK signals over 80 km of SSMF for single- and multi-channel scenarios, considering ECL and DFB laser as LO and 2.5 GHz channel spacing. The received power is always measured in the center channel, since it is the most affected by crosstalk and nonlinearities, thus emulating the worst case system condition. The considered BER limit of 3.8 × 10^{-3} corresponds to the 7% hard-decision forward error correction (HD-FEC) [54]. The transmitted power per channel is set at −6 dBm and the space between channels is 2.5 GHz. As observed, with an ECL as LO, the receiver sensitivity is −49.3 and −47.3 dBm for single- and multi-channel, respectively. We note that there is ∼3 dB improvement in the receiver sensitivity compared to our previous work [19] due to using a wide-band balun board after TIAs as well as AWG in the transmitter part.

For the DFB laser, the sensitivity drops to −47 and −44 dBm for single- and multi-channel, respectively, due to the phase noise of the laser. Fig. 9 presents two examples of the frequency offset over the time estimated by the real-time DSP, with the ECL and DFB laser local oscillator. As observed, the frequency offset behavior is similar for both lasers with a frequency variation of ∼1 kHz, which is reported due to the frequency control of the ECL in the OLT transmitter. However, the results conclude that the DFB is noisier than the ECL in terms of phase due to the ∼20 MHz-linewidth, which results in the receiver sensitivity penalty reported in Fig. 8. Note that the phase noise causes a high penalty in terms of CS in the phase recovery DSP algorithm. At

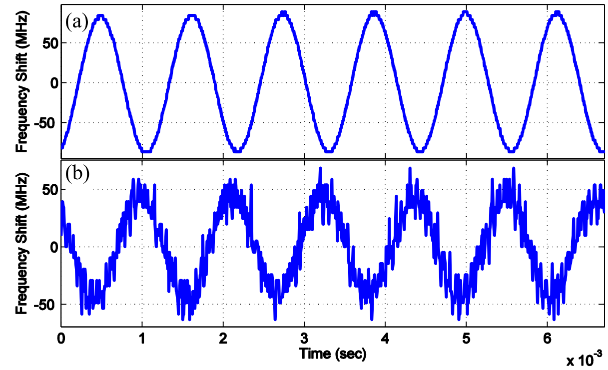

Fig. 9. Two random window examples of the frequency offset over the time estimated by the frequency recovery algorithm in the DSP considering (a) an ECL and (b) a DFB laser as LO.

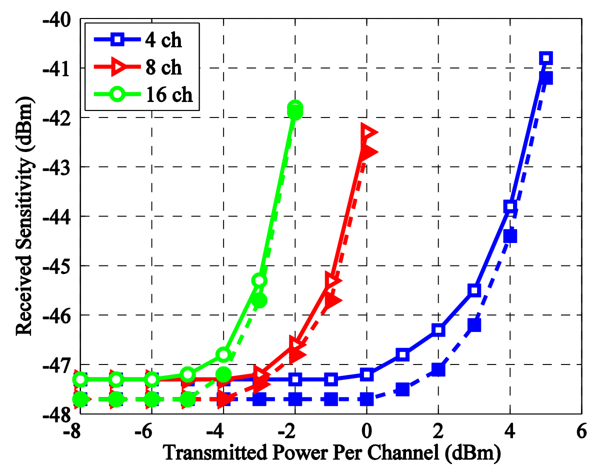

Fig. 10. ODN power budget of the UDWDM system: transmitted vs. received power per channel for a target BER of 3.8 × 10^{-3} for 4, 8 and 16 channels after 80 km fiber considering the ECL as LO. Solid lines + open markers: 2.5 GHz channel spacing. Dashed lines + filled markers: 3.125 GHz channels spacing.

the BER limit, a stable performance in terms of BER is however observed for several hours with the two lasers.

Fig. 10 characterizes the ODN power budget of the center channel for 4 (square marks), 8 (triangles marks) and 16 (circles marks) UDWDM channels and for 2.5 (solid lines) and 3.125 GHz (dashed lines) channel spacing. The modulation format considered is the DQPSK and the results illustrate the required received optical power by changing the transmitted power per UDWDM channels at the fiber input in order to maintain the target BER of 3.8 × 10^{-3}. For 16 channels, the maximum power budget observed is ∼43 dB, which is reported for a transmitted power of −4 dBm per channel. The receiver sensitivity penalty observed for the 2.5 GHz compared to the 3.125 GHz scenario is essentially due to some linear crosstalk between channels and a non-ideal analogue low-pass filtering at the receiver. Besides, in the TIA the PAPR of the signal is higher when the space between channels is 3.125 GHz. Between 4 and 8 channels, a penalty of around 4 dB in the ODN power budget is observed due to non-linear effects as FWM and XPM. This penalty is around 2 dB comparing 8 and 16 channels. These results imply the tradeoff between the power budget and the user count, as a way of ensuring grid flexibility as shown in Fig. 1.

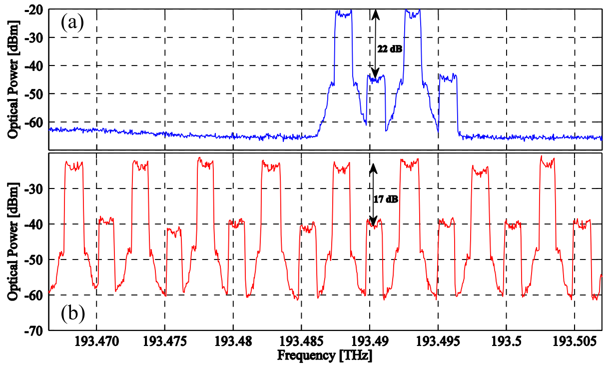

Fig. 11. Optical spectra of (a) 4 and (b) 16 channels at the input of 80 km fiber for 22-dB and 17-dB dynamic power range for DQPSK signals, respectively.

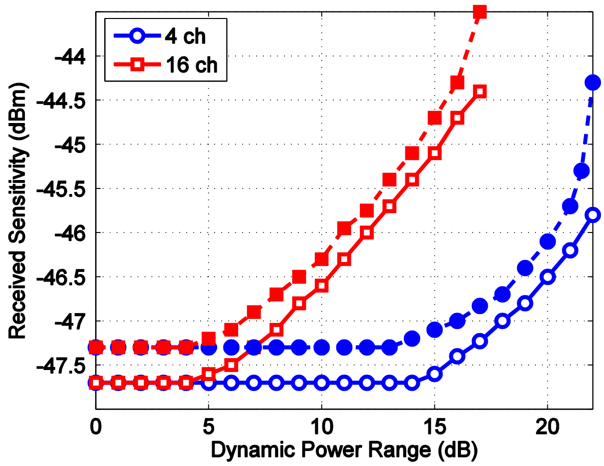

Fig. 12. Measured BER for the received power per channel of center UDWDM channels vs. dynamic power range at the input of 80 km fiber considering the ECL as LO. Solid lines + open markers: 2.5 GHz channel spacing. Dashed lines + filled markers: 3.125 GHz channels spacing.

Fig. 11 represents the optical spectrums of 4 and 16 channels UDWDM with 22 and 17 dB dynamic power range at the input of 80 km of SSMF, respectively, considering the US direction with DQPSK modulation format and channel spacing of 2.5 GHz. As highlighted in Fig. 1, the maximum unbalanced power between adjacent channels in US direction is an important parameter in the design of inside plant or outside plant of OANs. In a real scenario, due to the different link budgets between the OLT and each end-user, this dynamic power range should be defined. The obtained results are presented in Fig. 12 showing the penalty in the receiver sensitivity by changing the dynamic power range between adjacent channels in order to keep the BER at 3.8×10^{-3}. The TIA gain is optimized for each power. As observed for 16 channels, after 5 dB of dynamic power range the receiver sensitivity must be increased in order to keep the target BER. For 4 DQPSK channels, the same behavior happens, but after 14 dB of dynamic power range. This difference is due to the TIA gain, because when the peak-to-average power ratio of the signal is high, the TIA typically provides low electrical gain for each independent channel, resulting in a penalty for high number of channels. This penalty for 16 channels may be minimized with an analog electrical low-pass filter before the TIA.

In order to evaluate the flexibility of the system working with different modulation formats, Fig. 13 presents the receiver sensitivity for DQPSK and D8PSK signals for single- and multi-channel in 80 km of fiber. The results were obtained using a reconfigurable real-time DSP architecture with a space between channels of 2.5 GHz and considering the ECL as local oscillator. The sensitivity for DQPSK is the same as that reported in Fig. 8, while for D8PSK this drops to −41 and −37 dBm for single- and multi-channel, respectively, due to the low signal-to-noise ratio tolerance, along with a high CS penalty caused by phase noise.

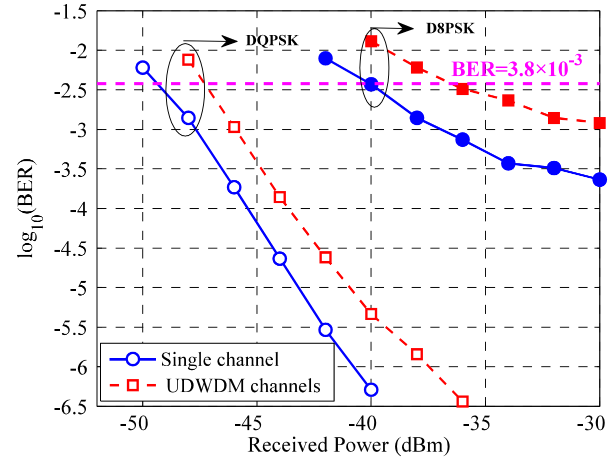

Fig. 13. Receiver sensitivity for single- and multi-channel for DQPSK and D8PSK signals after 80 km fiber considering the ECL as LO and 2.5 GHz channel spacing.

V. Conclusion

We have addressed the current trends in coherent access. The scarcity of spectrum, the required flexibility and constant evolution of PON requirements point to an excellent fitting to the use of coherent techniques in optical access. Its filter-less receiver operation, the inherent gain and its flexibility with regard to signal manipulation (higher order formats, pulse shaping, compensation mechanisms, etc.) allow taking advantage of the full potential of the fiber transmission in a flexible way. In addition, we experimentally characterized a digital coherent Nyquist UDWDM-PON system employing bidirectional 2.5 Gb/s DQPSK signals, with OLT/ONU receivers in real-time. The system performance regarding the power budget and dynamic power range for different number of channels were evaluated. The possibility of using a DFB laser as a local oscillator in the proposed system was investigated for use on any architecture scenario depending the number of users, power budget and cost of the network, although the wavelength stability/synchronization in UDWDM might still pose a challenge nowadays. Using a blind flexible 8-bit DSP architecture in a commercial FPGA and low-speed DAC/ADCs devices, i.e. 2.5 GSa/s and ~2 GHz analog bandwidth, the real-time flexible UDWDM system for coherent PON based on DQPSK and D8PSK modulation formats was demonstrated. Although the proposed single-polarization transmission/ detection paradigm is beneficial in terms of power consumption and cost compared to dual-polarization schematics, the associated issue of automatic polarization control still remains a challenging topic, worth of future research.

Taking advantage of the high spectral efficiency, flexibility and compatibility of coherent detection, combined with the recent advances in photonic integration that can substantially bring down the implementation cost, we expect that the coherent optical access networks will be a commercial reality in the future, supporting even more complex scenarios, such as high-order modulation formats and dual-polarization transmission.

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