Real-Time Bidirectional Coherent Nyquist UDWDM-PON Coexisting With Multiple Deployed Systems in Field-Trial

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***Abstract*—We experimentally characterize a bidirectional 2.5 Gb/s UDWDM-PON system based on Nyquist shaped DQPSK with digital signal processing in real time. The optical distribution network power budget of this system is evaluated and in coexistence of UDWDM channels with upstream TWDM-PON and RF video overlay signals, a set of optimum parameters and their impact on the network operation is driven. Additionally, we report the first field-trial of bidirectional coherent Nyquist UDWDM-PON using commercial real-time FPGA-based transceivers, coexisting with the deployed GPON, RF video overlay, and NG-PON2 technologies. A -44.5 dBm receiver sensitivity is achieved for 64×2.5 Gb/s DQPSK downstream channels and a 17 dB tolerance in dynamic power range of upstream channels is performed.**

***Index Terms*—Coherent access networks, digital signal processing, passive optical networks, Nyquist pulse shaping, ultra-dense wavelength division multiplexing.**

I. Introduction

DRIVEN by proliferation of heterogeneous bandwidth-consuming Internet services, passive optical network (PON) architectures have been noticeably evolving in the last ten years, providing improved availability, data rates and services. An evidence of this fast evolution is that both IEEE 802.3 and ITU-T together with the full services access network (FSAN) group are currently working towards the standardization of next-generation PON2 (NG-PON2) [1], [2]. Nevertheless, there are still a set of key requirements to be met in order to enable the successful and cost efficient deployment of future optical access network (F-OAN) technologies, namely in terms of spectral efficiency (SE), flexibility, extended reach, open access and heterogeneous service convergence.

Several access technologies are currently deployed in the field, and the choices have been to evolve from the legacy systems without discontinuity of the previous technology, in order to further exploit the investment [3]. This imposes a strong coexistence scenario, as depicted in Fig. 1(a). Additionally, as also shown in Fig. 1(b), spectral scarcity is now becoming a reality, since most of the low loss bands of the fiber are fully exploited. The Ethernet group, with Ethernet PON (EPON), has been quite successful in targeting cost due to its development methods. Gigabit PON (GPON) technology, driven by the ITU-T, has conquered several markets and achieved high take rate. XGPON was then developed to try and improve the data rate, and due to the lack of component maturity together with tighter filtering and laser requirements, some risks were already taken. From there, a new standard is now under finalization, the time and wavelength division multiplexing PON (TWDM-PON) or NG-PON2 [2], [4], representing a major change in the paradigm of previous technologies. These later trends show that new technological solutions such as orthogonal frequency-division multiplexing (OFDM) PON [5] or coherent ultra-dense WDM (UDWDM) PON [6], [7] can progressively be introduced in the network if they prove to meet the required cost and maturity.

The main technical difficulties faced by coherent detection in PON were related to the lower bit rates, which demanded stringent linewidth requirements at the local oscillator. Nowadays, the commercially available lasers have better performance and the data rates can be higher, which jointly relaxes the system requirements. Several research groups have carried out numerous efforts to explore this technology [6]–[11], demonstrating important benefits from using coherent detection in PON, including an extended optical distribution network (ODN) [8] and a very high number of channels supporting long distances in field-trials [9]. Projects like COCONUT [6], [10] have been focusing on getting simplified transmitter and receiver architectures for the optical line terminal (OLT) and optical network unit (ONU), even mixing concepts of non-return-to-zero (NRZ)

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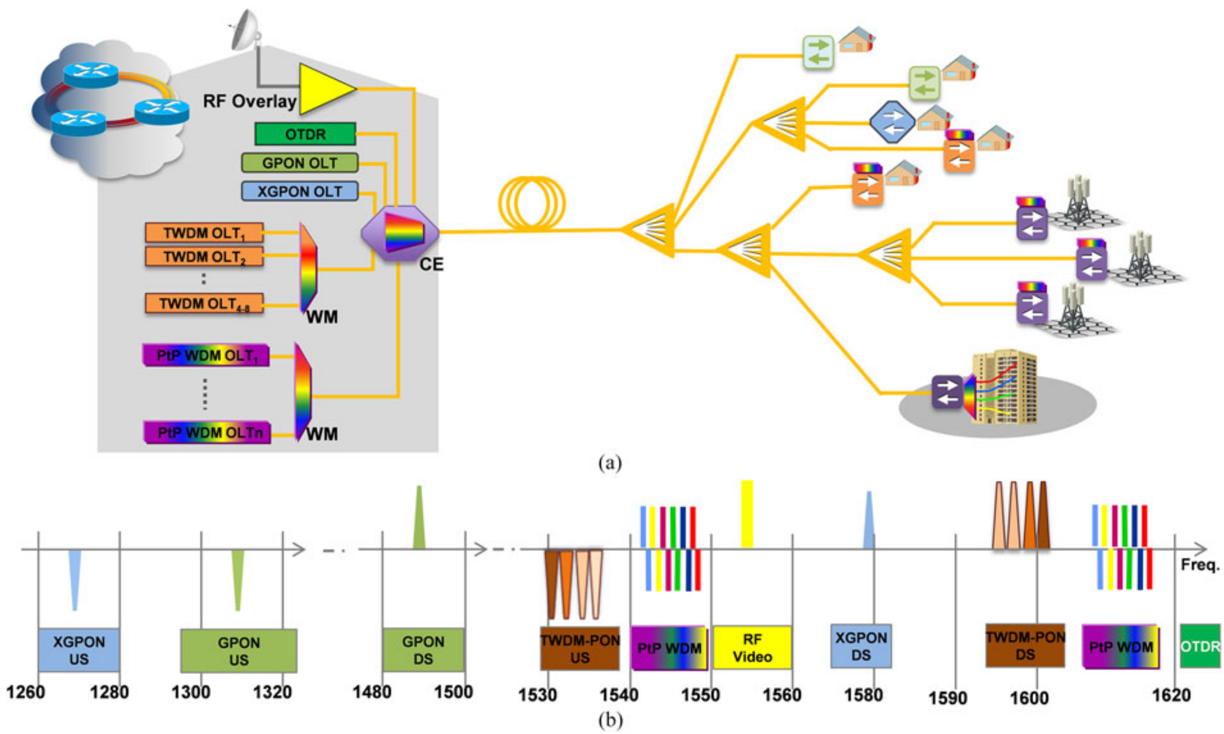

Fig. 1. (a) Multiple system configuration for F-OAN; (b) wavelength plan representation.

with simplified coherent receivers. These exploit, besides the higher sensitivity of coherent technology, the unique feature of filtering that may give the required flexibility to the networks.

Coherent UDWDM-PON based on advanced modulation formats and Nyquist pulse shaping has been shown to offer other benefits such as excellent SE with high aggregated capacity for flexible bandwidth OANs [11]. As a matter of fact, although Nyquist pulse shaping may bring some additional complexity for the transmitter and receiver [12]–[14], it allows for a much more efficient usage of the spectrum both in electrical and optical domains. Furthermore, it also brings important benefits in terms of reduction of Rayleigh back-scattering (RBS) and enhances the mitigation of nonlinear crosstalk between UDWDM channels due to cross-phase modulation (XPM) and four-wave mixing (FWM) [11], [15]. Recently, we have demonstrated the performance capabilities of Nyquist pulse shaping using quadrature phase-shift keying (QPSK) modulation in real-time operation for both OLT and ONU sides using simple 8-bit digital signal processing (DSP) supported by field-programmable gate arrays (FPGA) [14].

In this paper, which is an extension of our previous works [16], [17], we firstly experimentally characterize a bidirectional coherent UDWDM-PON system based on Nyquist shaped differential QPSK (DQPSK) signals over up to 80 km standard single mode fiber (SSMF) using DSP in real-time supported by commercials FPGAs on the optical laboratory test bed. Optimized power per channel in both directions is obtained and the ODN power budget is investigated. We analyze also the heterogeneous network scenarios with upstream (US) TWDM-PON channels and RF Video Overlay in order to characterize the required optical power per channel and guard-bands. The performance regarding nonlinear crosstalk between multi-systems, such as XPM, FWM and stimulated Raman scattering (SRS), is evaluated. Building upon this lab experiment, we demonstrate a digital coherent Nyquist UDWDM-PON field-trial supporting 64 downstream (DS) and 3 US Nyquist DQPSK channels at 2.5 Gb/s. Compared to the state of the art coherent PON trial reported in ref. [9], our work improves the SE by a factor of more than 4, since the UDWDM transports bidirectional 2×2.5 Gb/s in 2.5 GHz optical band per user (2 b/s/Hz). The network performance is characterized in terms of the receiver sensitivity and dynamic power range in a heterogeneous scenario including already deployed GPON, RF video overlay and NG-PON2 terminal equipment.

The paper is organized as follows. Section II presents the experimental setup and the DSP subsystems used to characterize the UDWDM-PON system. The experimental results are discussed in section III, including the assessment of the total ODN power budget of the DS channels and the coexistence issues with US TWDM-PON and RF video overlay systems. Section IV presents the field-trial demonstration with a 4×16 and three DQPSK channels at 2.5 Gb/s in the DS and US directions, respectively.

II. Experimental Setup and DSP Subsystems

A. *Experimental Setup*

The experimental setup present in Fig. 2(a) is used to study the feasibility of coherent Nyquist UDWDM-PON employing DQPSK modulation format. At the OLT, a tunable external cavity laser (ECL) (<100 kHz–linewidth) is used as optical source (λ_1), injected into an IQ modulator (IQM) driven by the Tx_1 transmitter, which generates the 2.5 Gb/s DQPSK electrical signal. In order to emulate a DS UDWDM grid, an optical signal

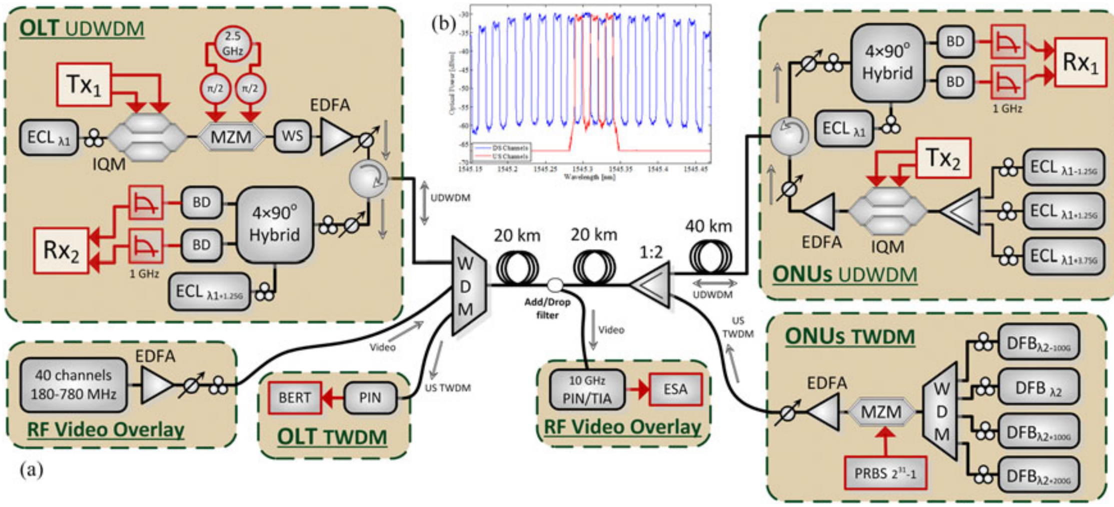

Fig. 2. (a) Experimental setup for UDWDM-PON coexisting with US TWDM-PON and RF video overlay systems; (b) DS and US spectrum of the UDWDM-PON system (BERT: bit-error rate tester; TIA: transimpedance amplifier).

comb generator based on a Mach-Zehnder modulator (MZM) [18], controlled by a radio frequency (RF), is used to generate 16 UDWDM channels with a channel spacing of 2.5 GHz. At the output of the comb, the band of interest is filtered by one wave-shaper (WS) with a 50 GHz band-pass filter. The decorrelation between the 16 channels is ensured by the use of a comb after the modulator. The input fiber optical power is set by an Erbium doped fiber amplifier (EDFA) and a variable optical attenuator (VOA), followed by a circulator to separate US and DS channels.

The total optical signal is transmitted over 80 km of SSMF. At the ONU side of UDWDM system, a VOA sets the received power and then the 16 channels are coherently detected using a $4 \times 90°$ optical hybrid with an ECL local oscillator (<100 kHz–linewidth) (intradyne detection). The in-phase and quadrature optical signals (single polarization) are converted to the electrical domain using a pair of balanced detectors (BD), filtered by 1 GHz low-pass filter (to select only a single DQPSK channel), and then compensated and demodulated in the real-time electrical receiver Rx_1. Given that the receiver is polarization sensitive, a set of polarization controllers are used to align the received polarization state with that of the local oscillator. We note that polarization dependence of this scheme can be avoided using optical polarization tracking in the local oscillator. For the US direction, a similar methodology is used. Instead of the comb generator to emulate the UDWDM grid, we are using three ECLs, giving a total of three US channels with a channel spacing of 2.5 GHz and shifted by 1.25 GHz from the DS wavelengths in order to mitigate back reflection crosstalk. The detection in the OLT is similar to the ONU. The spectrum of the 16 DS plus the 3 US channels is shown in Fig. 2(b).

To emulate a coexistence scenario with the DS UDWDM signal, an analog RF video overlay signal with RF channels from 180 to 780 MHz at 1556 nm was multiplexed via a WDM filter. After 20 km, the video signal was dropped by an add/drop filter and then detected directly by a 10 GHz PIN photodetector. The resulting electrical signal was measured by an 8 GHz electrical spectrum analyzer (ESA) with the resolution bandwidth

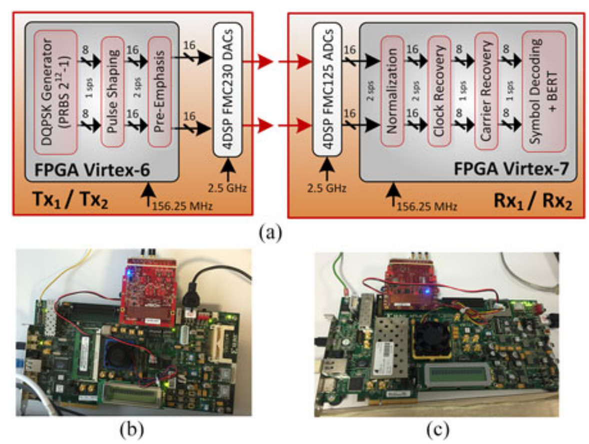

Fig. 3. (a) Simple DSP for OLT/ONU transmitters and receivers; (b) picture of the electrical transmitters (ML605 + FMC230 board); (c) picture of the electrical receivers (VC707 + FMC125 board).

(RBW) of 300 kHz and video bandwidth (VBW) of 1 kHz. Additionally, to evaluate the coexistence with an US TWDM-PON system, the UDWDM signal is combined with 4×2.5 or 10 Gb/s NRZ channels via a 1:2 coupler over 40 km of fiber. The four TWDM channels were generated with four distributed feedback lasers (DFBs), spaced by 100 GHz between 1530.33 and 1532.68 nm and modulated with NRZ modulation format (with a 2^{31}–1 PRBS) in a single MZM, with 10 and 8 dB extinction ratio for 2.5 and 10 Gb/s, respectively. The optical power is controlled by an EDFA and VOA. At the OLT, the TWDM signals were directly detected after demultiplexing from UDWDM signal.

B. DSP Subsystems

The DSP architecture applied in this paper to modulate and demodulate the DQPSK signal is depicted in Fig. 3(a). The design is suitable for both DS and US directions and considers intradyne coherent detection. In order to optimize optical source at the OLT/ONU, commercial UDWDM transceivers may require optical heterodyne detection configurations [7]. In that case, to relax analog bandwidth requirements in both DACs/ADCs devices, RF combiners can be used to shift the DS from the US wavelengths.

The transmitter side of both OLT (Tx_1 for the DS signal) and ONU (Tx_2 for the US signal) includes a DQPSK generator with a pseudo-random binary sequence (PRBS) of 2^{12}–1, followed by a RC filter (0.1 roll-off factor) applied using a set of 14-bit multiplier-free finite impulse response (FIR) filters with 32-tap resolution [14]. The oversampling is set at two samples per symbol (SPS). Finally, a pre-emphasis filter based on 3-tap FIR filters with 8-bit resolution is also applied in order to mitigate bandwidth limitations. All the DSP design is implemented in a Virtex-6 FPGA (ML605 board) working at 156.25 MHz, leading to a degree of parallelization (DOP) of 16 in order to enable real-time processing at 2.5 Gsa/s. The digital signal is converted to analog domain using two 14-bit 2.5 Gsa/s DACs (4DSP FMC230 at 1.4 GHz analog bandwidth).

At the OLT (Rx_2 for the US) and ONU (Rx_1 for the DS) receiver, the signal is sampled by two 8-bit 2.5 Gsa/s ADCs (4DSP FMC125 at 2 GHz bandwidth) and the DSP is supported by a Virtex-7 FPGA (VC707 board), again with a DOP of 16 (FPGA clock at 156.25 MHz). Based in a feedback architecture, the amplitude normalization is applied to improve the dynamic range of the DSP and then, the ideal sampling instant of the ADC is compensated using linear interpolation based on 2-tap FIR filters with an 8-bit design, supported by feedback timing error estimation based on the Gardner power formulation. In the transmitter side, the bit rate was set at 2.49995 Gb/s in order to optimize the performance of the previous algorithm. Carrier recovery is performed using one SPS with two separated Mth-power schemes digital subsystems based on feed-forward controls: (1) frequency recovery, using the differential phase-based method (averaged in independent windows of 512 symbols), and (2) phase recovery based on the Viterbi & Viterbi algorithm (averaged over 8 symbols), both implemented using only 8-bit resolution. Details of the DSP can be found in [14]. Finally, after DQPSK symbol decoding, the bit-error rate (BER) is measured by means of bit error counting in real-time. Pictures of the transmitter and receiver are shown in Fig. 3(b) and (c), respectively.

III. Experimental Results and Discussion

Fig. 4 evaluates the ODN power budget of the real-time UDWDM-PON system. The results represent the transmitted power per DS channel versus the required receiver sensitivity of the center DS channel to maintain the considered BER threshold limit of 3.8×10^{-3}, which is the considered forward error correction limit. The center channel is more severely affected by crosstalk and nonlinear effects, and thus provides a lower bound for the system performance. The power of the US channels was set at −6 dBm and we are testing a link with 20, 40 and 80 km. The US TWDM-PON and the RF Video Overlay systems are not considered. For 80 km, the maximum ODN power budget is reported for around −2 dBm of transmitted power (−42.7 dBm of receiver sensitivity), yielding a total optical power budget of 40.7 dB.

For 20 km of fiber, the maximum ODN power budget is extended to 41.5 dB, corresponding to 0 dBm of transmitted power and −41.5 dBm of receiver sensitivity. Nevertheless, a transmitter power per channel below than −4 dBm should be used to achieve reduced crosstalk between DS/US channels [17], resulting in a ODN power budget of 39.5 dB. The penalty for 80 km scenario is observed due essentially to the more crosstalk and FWM nonlinear effect between DS channels with the extended optical link.

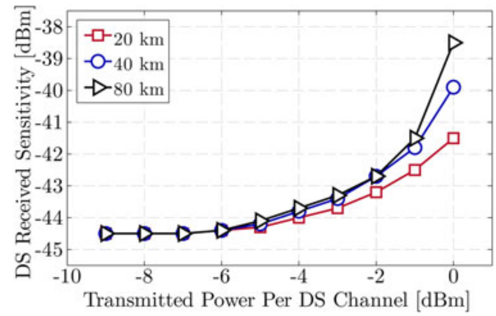

Fig. 4. ODN power budget of the UDWDM system: transmitted vs. received power per DS channel for a target BER of 3.8×10^{-3}: 20, 40 and 80 km.

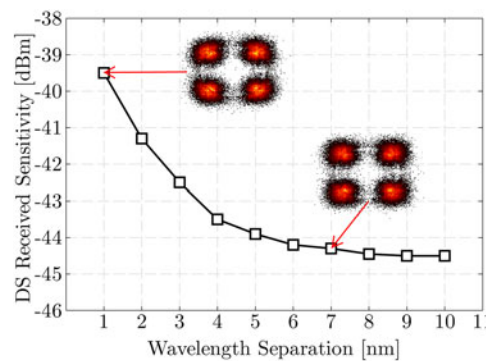

Fig. 5. Required received sensitivity of the center DS UDWDM channel for a target BER of 3.8×10^{-3} with different wavelength separation to RF Video Overlay system at 1556 nm. The optical power of analog RF video overlay signal was set at 16.5 dBm at the input of 20 km fiber.

Fig. 5 depicts the receiver sensitivity of the center DS UDWDM channel required to maintaining a target BER of 3.8×10^{-3}, when the wavelength spacing for the RF Video Overlay system is changed. The video signal is located at 1556 nm and to vary the space between the two systems, the center wavelength λ_1 of the DS UDWDM system is swept between 1546 and 1555 nm. The power of the US channels was set at −6 dBm and the US TWDM-PON system is not considered. As can be concluded, for a wavelength spacing higher than 7 nm, no significant interferences in the UDWDM is observed from the RF Video Overlay system.

Fig. 6 makes a similar assessment, indicating the receiver sensitivity of the center US UDWDM channel (λ_1 with 1.25 GHz shifting) required to maintain at BER of 3.8×10^{-3}, considering different wavelength separation relatively to the US TWDM-PON system. The four US TWDM channels are located between 1530.33 and 1532.68 nm. To vary the spacing between the two PON systems, the center wavelength $\lambda_{1\,+\,1.25\mathrm{G}}$ of the US UDWDM is swept between ∼1535 and ∼1544 nm. The power of the DS channels was set at −6 dBm and the RF Video

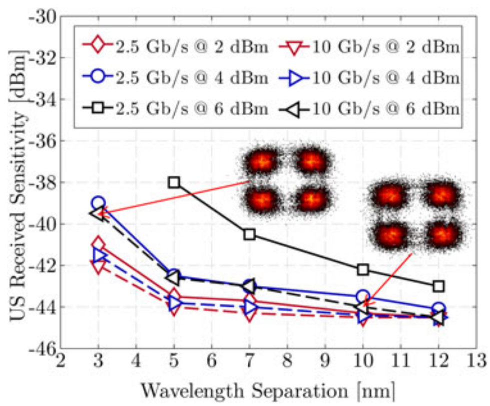

Fig. 6. Required received sensitivity at of the center US UDWDM channel at BER of 3.8×10^{-3} with different wavelength separation to US TWDM system. The four US TWDM channels are located between 1530.33 and 1532.68 nm with optical power variation from 2 dBm per channel to 6 dBm per channel in the input of 40 km fiber and after the 1:2 coupler.

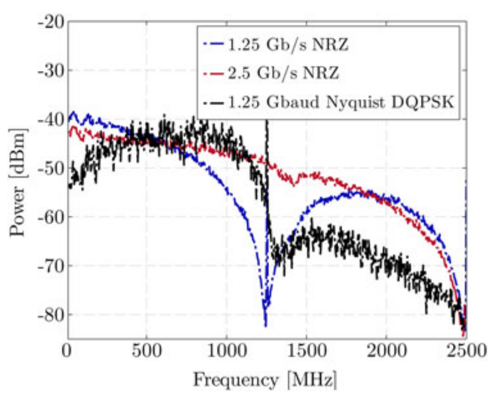

Fig. 7. Measured PSD of 1.25 Gb/s NRZ, 2.5 Gb/s NRZ and 2.5 Gb/s DQPSK signals (with equal optical power) obtained by direct detection.

Overlay system is turned off. The US sensitivity results show that the required guard band has to be more than ∼7 nm when the US TWDM signals have 4 dBm launch power. The 2.5 Gb/s (solid lines) case is also worse than the 10 Gb/s (dashed lines) TWDM due to enhanced XPM nonlinear effects at lower data rates. For guard bands higher than ∼10 nm, there is no penalty when the power are 4 and 6 dBm per TWDM channels for both 4×2.5 and 4×10 Gb/s systems, respectively. Using 10 Gb/s TWDM channels, we also evaluate the required guard-bands for the UDWDM-PON system if is located at L-band as shown in Fig. 1(b).

Finally, to evaluate the SRS from the UDWDM system on the low frequency channel of the RF Video Overlay system, Fig. 7 shows the electrical power spectral density (PSD) of a 2.5 Gb/s (1.25 GBd) Nyquist DQPSK and 1.25 and 2.5 Gb/s NRZ signals after direct detection. As observed, due to constant optical intensity of the Nyquist DQPSK signal, for lower frequency (<100 MHz) there is more than 10 dB lower PSD compared to 1.25 Gb/s NRZ (same equivalent symbol rate) that results on reduced SRS on the video signals [19]. Then, we measured the Raman crosstalk of the 16 UDWDM channels (0 dBm per channel—total power of 12 dBm) on the RF Video Overlay system over 20 km of SSMF for different wavelength

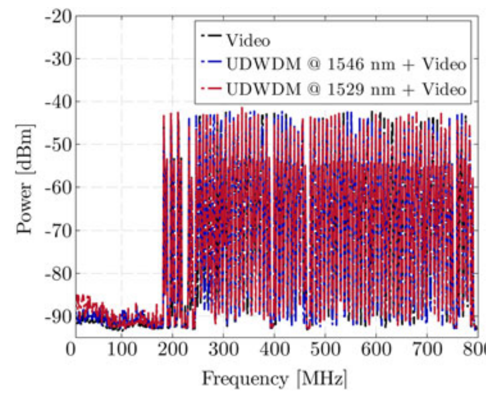

Fig. 8. The SRS crosstalk of the 16 DS UDWDM channels at 1546 and 1529 nm (with 0 dBm per channel) on 8 dBm RF Video Overlay system at 1556 nm after 20 km fiber with −3 dBm of received power.

separations (10 to 28 nm—the ECL used for the UDWDM is fully tunable in the C-band). Fig. 8 depicts the results of the carrier-to-Raman-crosstalk ratio of the video channels. As shown, there is a minimal SRS on the video signal over 20 km for 10 nm separation between the UDWDM and the RF Video Overlay systems (the approximate spacing for a UDWDM technology located at the C-band). For instance, there is below than 1 dB carrier-to-Raman-crosstalk ratio at 55 MHz (the lowest frequency channel suffered the largest SRS-induced crosstalk) channel of analogue video signal. Note that, if 64 UDWDM channels are considered with −6 dBm per channel (12 dBm total optical power), we should also obtain a minimal SRS crosstalk on RF Video channels [17]. In addition, Fig. 8 depicts a non-negligible Raman crosstalk for higher wavelength spacing, e.g., 28 nm of wavelength separation. It is worth mentioning that with the UDWDM-PON system located in the L-band (>50 nm of wavelength spacing), which is one available bandwidth for this technology (see Fig. 1(b)), the power per channel and number of the channels should be optimized.

IV. Field-Trial Demonstration

A. Field-Trial Setup

The setup used for the field-trial validation of the UDWDM-PON system is depicted in Fig. 9(a). At the UDWDM OLT, four optical carriers ($\lambda_1, \lambda_2, \lambda_3, \lambda_4$) are generated by four ECLs (<100 kHz–linewidth) separated by 50 GHz (λ_2 at ∼1545 nm). These carriers are then injected into an IQM driven by the Tx_1 transmitter, which generates a real-time 2.5 Gb/s DQPSK electrical signal. In order to emulate the DS UDWDM grid, an optical signal comb generator based on a MZM controlled by a radio frequency signal is used to generate the 4×16 UDWDM channels spaced by 2.5 GHz for each carrier. The remaining transmitter is similar to the experimental setup of Fig. 2(a). The total optical signal is transmitted over 8.4 km of field deployed fiber (with 16 dB total loss, which is observed due to optical splitter and various connectors that are installed over this deployed link), crossing Aveiro city, Portugal (satellite view in Fig. 9(c)), plus 50 km of SSMF (10.5 dB loss) in the lab. The receiver at the UDWDM ONU and the configuration of the US signal are fully similar to the setup of Fig. 2(a).

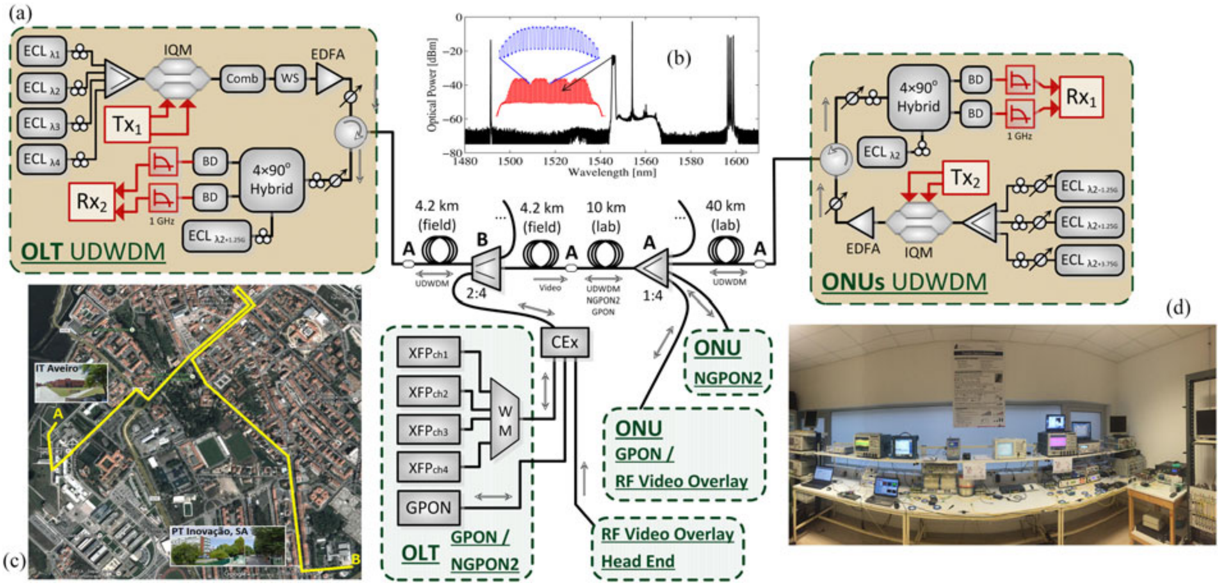

Fig. 9. (a) Field-trial setup for UDWDM-PON coexisting with GPON, NG-PON2 and RF video overlay technologies; (b) optical DS spectra; (c) satellite view of the field-trial connection; (d) laboratory infrastructure.

Together with our system, we study the coexistence with three commercial PON technologies from PT Inovação e Sistemas. The DS traffic of GPON (B + class) and NG-PON2 (N2 class) technologies are generated at the same OLT (pay-as-you-grow). The DS GPON operates at 2.5 Gb/s with 5 dBm (centered at 1490 nm), and DS NG-PON2 at 4×10 Gb/s with 8 dBm of transmitted power per channel (wavelengths of 1596.34, 1597.19, 1598.04 and 1598.89 nm). The RF video overlay uses CATV (47–820 MHz) and IF-SAT (950–2150 MHz) components and is located at 1554 nm with 20 dBm optical power. DS NG-PON2 wavelengths are multiplexed using a wavelength multiplexer device, and the DS GPON, DS NG-PON2 and RF Video Overlay are multiplexed using a coexistence element (CEx). These are finally merged with the UDWDM system using a 2:4 optical splitter and then transmitted over 4.2 km of field deployed fiber plus 10 km of lab fiber. All the four systems are then split using a 1:4 optical splitter. The US traffic of GPON operates at 1.25 Gb/s with 5 dBm optical power (located at 1310 nm), and the US NG-PON2 consists in one channel up to 2.5 Gb/s with 4 dBm. The NG-PON2 (N2 class type A link) uses a fully tunable ONU (ITU-T G.989.2), with wavelengths between 1532–1540 nm.

B. Results

Fig. 10 shows the field-trial BER results depending on receiver sensitivity for both DS and US signals of the UDWDM system, considering the coexistence of all other commercial PON technologies. The transmitted power per channel of the UDWDM was set at -4 dBm for both DS and US channels, considering the ODN power budget optimization performed in the section III. We report a sensitivity of -44.5 dBm in the measured DS channels (located in the second set of 16 UDWDM channels at λ_2) for a target BER of 3.8×10^{-3}. A penalty of around 1 dB is reported in the US direction due to DS back reflections at the beginning of the transmission system (in the field deployed fiber). Similar results have been observed for the

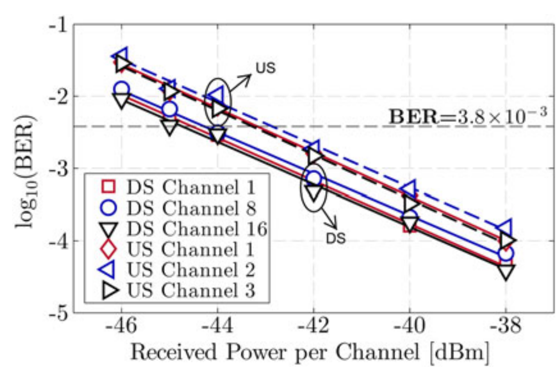

Fig. 10. Measured receiver sensitivity for different DS and US channels in the second set of 16 UDWDM channels (λ_2).

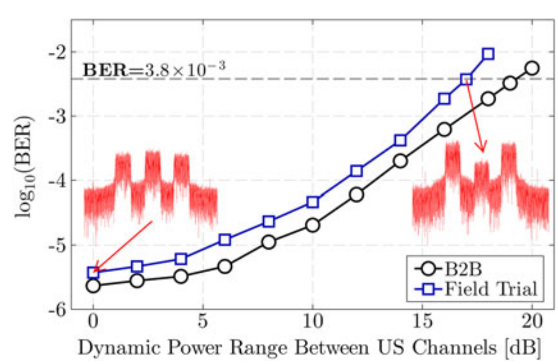

Fig. 11. Dynamic power range for the center US channel.

remaining three sets of 16 DS UDWDM channels (λ_1, λ_3 and λ_4). At the BER limit, a stable performance has been observed by several hours.

Fig. 11 represents the dynamic power range of the center US channel ($\lambda 2$ with 1.25 GHz shifting) in the back-to-back (B2B) and field-trial scenarios coexisting with all the deployed PON technologies. The dynamic power range characterizes the maximum power unbalance between adjacent channels, which is an important consideration for the US traffic due to the different link budget between the OLT and each end-user in a real scenario. To report these results, the last 40 km of optical fiber in lab are not considered and the transmitted power per US channel was fixed at -4 dBm. The dynamic power range is obtained by decreasing the transmitted power of the center US channel using a VOA before IQM modulator as shown in Fig. 9(a). The obtained results show that the maximum dynamic power range that can be supported by the center US channel (by optimizing the US received power) is 17 dB for the field-trial scenario. The insets of Fig. 10 show the electrical spectra obtained by the sampling oscilloscope, corresponding to 0 dB and 17 dB dynamic power range.

In addition, we have analyzed the impact of the US NG-PON2 (at 0 dBm per channel after the 1:4 splitter) in burst-mode operation on the US UDWDM channels. By changing the burst data-rate (100 Mb/s, 1 Gb/s, 2.5 Gb/s) and the wavelength separation between the US NG-PON2 and UDWDM system from 3 nm to 10 nm, we have not observed any penalty on the sensitivity of the US UDWDM channels. During the experiment, no visible interference or signal degradation has been observed between the UDWDM and the remaining commercial services, thus demonstrating the practical feasibility of the proposed coexistence scenario.

V. Conclusion

We characterized a bidirectional 2.5 Gb/s UDWDM-PON system based on Nyquist DQPSK in real-time. An optimum ODN power budget of $\sim$39.5 dB was achieved with reduced penalty after 80-km reach. In addition, reduced impact of cross-phase modulation and SRS with optimum guard band between US TWDM-PON channels and RF Video Overlay systems resulted in spectral efficiency with high aggregated capacity. Additionally, we demonstrated the first field-trial implementation of digital bidirectional coherent Nyquist UDWDM-PON system employing bidirectional 2.5 Gb/s DQPSK signals, with OLT/ONU transmitters and receivers operating in real-time and in coexistence with deployed GPON, RF Video Overlay and NG-PON2 technologies. We achieved a -44.5 dBm receiver sensitivity over 8.4 km of fiber deployed in Aveiro city, Portugal, plus 50 km of spooled SSMF. In conjugation with commercial FPGA and low-speed DAC/ADC devices (2.5 Gsa/s at $<$2 GHz), we demonstrated a 17 dB tolerance in dynamic power range for the US UDWDM channels, thus relaxing the requirements for flexible network configuration.

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