1Gbps full-duplex links for ultra-dense-WDM 6.25GHz frequency slots in optical metro-access networks

Jose A. Altabas,[1,*] David Izquierdo,[1,2] Jose A. Lazaro,[3] Adolfo Lerin,[3] Felix Sotelo,[1] and Ignacio Garces[1]

[1]*Grupo de Tecnologías Fotónicas (GTF), Aragon Institute of Engineering Research (I3A), Universidad de Zaragoza, Mariano Esquillor ed. I + D + i, Zaragoza, 50018, Spain*

[2]*Centro Universitario de la Defensa (CUD), Academia General Militar, Carretera de Huesca s/n, Zaragoza, 50090, Spain*

[3]*Grupo de Comunicaciones Ópticas (GCO), Universitat Politècnica de Catalunya, Jordi Girona 31, Barcelona, 08034, Spain*

**jaltabas@unizar.es*

Abstract: 1Gbps full-duplex optical links for 6.25GHz ultra dense WDM frequency slots are demonstrated and optimized for cost-effective metro-access networks. The OLT-ONU downlinks are based on 1Gbps Nyquist-DPSK using MZM and single-detector heterodyne reception obtaining a sensitivity of −52dBm. The ONU-OLT uplinks are based on 1Gbps NRZ-DPSK by directly phase modulated DFB and also single-detector heterodyne reception obtaining same sensitivity of −52dBm. The power budget of full-duplex link is 43dB. These proposed links can provide service to 16 (32) users at each 100 (200) GHz WDM channel.

OCIS codes: (060.1660) Coherent communications; (060.2360) Fiber optics links and subsystems; (060.5060) Phase modulation.

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1. Introduction

The telecommunications scenario is quickly evolving during the last years. Growing cloud and multimedia streaming services are creating new communication frameworks, requiring flexible architectures in order to enable scalability while supporting a high level of dynamic connectivity. While the core remains as a multi-layer packet over optical network, metro networks are merging with access networks, as depicted in Fig. 1, and evolving towards an all-optical solution [1, 2]. In these networks, the Optical Line Terminal (OLT) acts just like another node in the metro network, while the users/subscribers are connected through a Passive Optical Network (PON), having a tree topology in Fig. 1, which is linked to the metro access through a Reconfigurable Optical Add-Drop Multiplexer (ROADM) node. Each PON uses a different WDM channel that is shared among all the subscribers connected through the same PON, using narrower ultra dense WDM (udWDM) channels for both up and down links, as is depicted in Fig. 1. Meanwhile, the metro network is transparent transmitting the entire optical spectrum within a given optical transmission band between the different nodes in such a way that each ROADM extracts the WDM channel of its child PON from the network. The connection between the OLT/Node and each user/subscriber ONU (Optical Network Unit) is established using a different udWDM channel or frequency slot for each user, which travels unalterable (without any wavelength conversion) in the entire merged network.

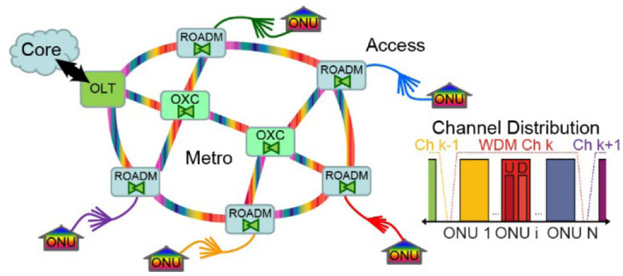

Fig. 1. All-optical access/metro network scenario. Inlet: proposed flexible udWDM full-duplex frequency slot division.

Additionally, the increasing traffic demand is pushing an even more efficient use of optical network resources by developing Elastic/Flexible Optical Networks and bandwidth optimization. Lately, this has been mainly done by several techniques, namely orthogonal frequency division multiplexing (OFDM) [3] and Nyquist pulse-shaping [4]. Both methods can be implemented using flexible digital transmitters and receivers [5] and require very sophisticated Digital Signal Processing (DSP), but are expected to give: the best performance and the highest flexibility in the near future; and also adaptive modulation format to ensure successful transmission under varying link conditions.

In this paper we propose a passive optical access network that uses 6.25GHz optical frequency slots for each user/subscriber where 1Gbps full-duplex channel are obtained for down (from OLT to ONU) and up (from ONU to OLT) streams using Differential Binary Phase Shift Keying (DPSK) modulation in a udWDM scheme. Using the proposed scheme in combination with Nyquist pulse shaping technique, 16 (32) frequency slots can be allocated within each ITU 100GHz (200GHz) wide WDM channel. The presented coherent links will allow an increment of the number of users of the current access networks. Therefore, the deployment and the maintenance costs of these networks will be shared by a greater number of users so the cost per user will be reduced.

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Two different flexible digital transceivers (transmitter and receiver) have been developed and are presented in this paper. As flexible digital transceivers, the bit rate can be adapted to user's requirements. 1Gbps full-duplex channel has been detailed measured as a reference for testing minimum size of the frequency slots. The ONU transmitter is based on cost-effective light sources and uses NRZ pulse-shaping while the OLT uses an externally modulated tunable light source and Nyquist pulse-shaping technique to provide a higher spectral efficiency. Both OLT and ONU receivers are based on a reduced-complexity heterodyne receiver compatible with a polarization independent version.

2. Experimental setup

The experimental setup for the evaluation of the proposed merged network is depicted in Fig. 2, where an OLT can serve to several ONUs of a PON using phase modulation and coherent detection in udWDM full-duplex 1Gbps channels. We will show that it is possible to allocate 16 of those channels in a 100GHz wide ITU grid channel. The full-duplex link between OLT and an ONU of the PON will be evaluated for sensitivity measurements including additional ONU implemented for interchannel interference measurements.

The OLT transmitter is based on an external cavity, 100kHz linewidth, Tuneable Laser Source (TLS), modulated by a Mach-Zehnder Modulator (MZM). The TLS is used to adjust its wavelength inside the frequency slot for these measurements, but a wavelength thermally-tunable Distributed Feedback Laser (DFB) can be used instead of the TLS. The MZM is set at the minimum transmission point for phase modulation and is thermally controlled to ensure its stability. In this configuration, the OLT would need as many transmitters as served ONUs, but this configuration can be simplified combining several user downstream data by electrical subcarrier division multiplexing previous to its optical modulation by a high bandwidth I/Q modulator [6].

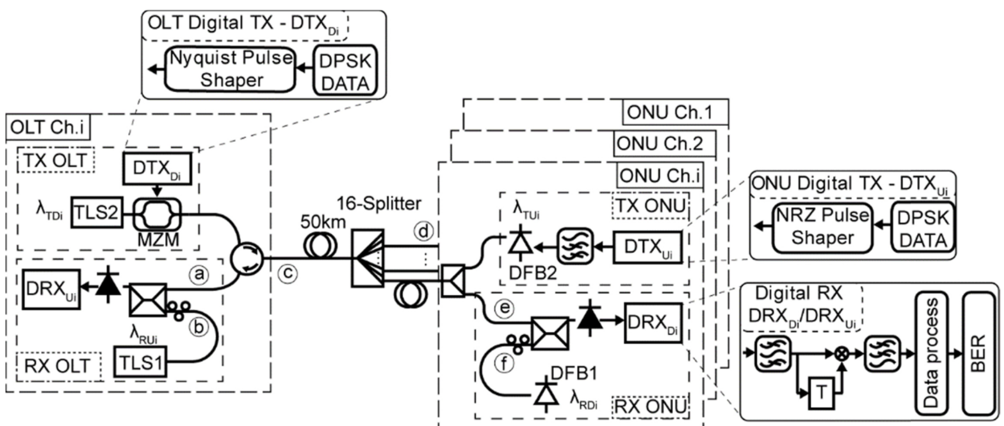

Fig. 2. Experimental setup for the evaluation of the optical link. P_{RX} at (a) and (e) points, P_{LO} at the (b) and (f) point and P_{TX} at (c) and (d) points.

The ONU transmitter consists of a DFB, which is direct-phase-modulated using its chirp through a previously equalized signal [7]. The cost-effective DFB used for the measurements presents a relative wide linewidth, in the range of 10MHz. The DFB emission wavelength is thermally tuned to achieve the channel spacing and flexible grid requirements inside the WDM channel. These requirements, fine tuning and long time stability, can be ensured using Proportional Integral Derivative (PID) thermal controllers with a ± 0.01°C resolution and stability. The used DFB frequency variation with temperature is 10GHz/°C, similar to other cost-effective DFBs [8], so the ± 0.01°C PID resolution will ensure a wavelength stability

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around 100MHz. If higher stability is required, the PID controller may be upgraded using a low bandwidth photodiode with an etalon [9].

Both optical transmitters (OLT and ONU) use a Digital Transmitter (DTX) unit, where the data is differentially encoded and shaped to achieve maximum performance for the 1Gbps up and down data-streams. The transmitted symbols in the OLT Digital Transmitter (DTX_{Di}) are filtered using a Nyquist Pulse Shaper filter with 12-symbols filter length and zero roll-off factor. The transmitted symbols generated in the ONU Digital Transmitter (DTX_{Ui}) are bipolar Non Return to Zero (NRZ) coded and high-pass filtered to obtain the phase modulation of the laser [7, 10]. The DTX are implemented in MATLAB™ and the electrical signals are generated by a 12GSa/s Arbitrary Waveform Generator.

The link between the OLT and the ONUs is fully passive and it implemented by on 50Km of Standard Single Mode Fiber (SSMF) and a 16-splitter for sharing out the data to the users. It represents one of the PON sections shown in Fig. 1.

Both receivers are based on a single photodetector heterodyne detection configuration. In this configuration the received signal is coupled with the Local Oscillators (LO), mixed in the photodetector and filtered. The LO used in the OLT receiver is an external cavity TLS with similar characteristics to the one used for the transmitter, and as was pointed out for the OLT transmission, it can be substituted by a DFB presenting enough wavelength stability without BER penalty. Besides, the ONU uses the same DFB model for both: the receiver and transmitter. Both LOs have been configured to provide the same optical power of + 4.2dBm. The emission wavelength of these LOs is tuned Δλ away from the received central wavelength of its uDWDM channel, being $\lambda_{RDi} = \lambda_{TDi} \pm \Delta\lambda$ at the ONU and $\lambda_{RUi} = \lambda_{TUi} \pm \Delta\lambda$ at the OLT. The coherent detection is highly dependent on the polarization difference between signal an LO, so we had to adequately control the polarization of the signal for our measurements, but our system is easily upgradeable to a polarization independent heterodyne receiver like the proposed in [11].

The received signal has been optically down-converted in the heterodyne detector to an Intermediate Frequency (IF) equal to the frequency shift between the LO and the central wavelength of the received signal (Δλ). 1GHz and 2GHz have been chosen as the heterodyne IFs because they represent a compromise between: a) an optimum separation between the 1Gbps signal and the LO to obtain the best BER performance (IF = n·Rb, with n integer); and b) the achievement of the narrowest frequency slot for each user. The obtained IF signal is amplified and, digitalized using a 40GSa/s Digital Oscilloscope with a 2.5GHz electrical bandwidth. However, the signal can be digitalized with a lower sampling rate down to 10GSa/s without BER penalty. The first step in the digital processing is the bandpass filtering of the digitalized signal in order to reduce the noise and eliminate the adjacent channels and the non-heterodyned part of the received signal produced by the rest of the channels that are reaching the detector out of band of the heterodyne signal. The demodulation of the DPSK format, is made by multiplying the signal with the same signal delayed by one symbol and by lowpass filtering, Fig. 2. Finally, the bit error rate (BER) is calculated comparing the received data-stream with the transmitted one.

2.1 Experimental digital receiver filtering optimization

The digital filters inside each DRX have been optimized separately to maximize the sensitivity in the receivers. The Band Pass Filter (BPF) and Low Pass Filter (LPF) bandwidths at the ONU (DRX_{Di}) have been optimized to minimize the BER for the two different heterodyne frequencies (1GHz and 2GHz) for a received Nyquist-DPSK downlink signal of −48dBm. The central frequencies of the BPF are fixed to the heterodyne frequencies. The minimum BER, as shown by red crosses in Fig. 3, is achieved for a BPF bandwidth of 1.3GHz (IF = 1GHz) and 1.5GHz (IF = 2GHz), respectively. The minimum BER for the case of 1GHz IF is higher than the BER of the 2GHz case due to the reduction of the BPF bandwidth needed to eliminate the non-heterodyne signal that is closer to the signal of interest

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for the 1GHz IF than in the 2GHz IF. On the other hand, the BER is minimum and stabilized for both heterodyne frequencies for LPF bandwidths higher than 1.25GHz in both cases as shown in Fig. 3.

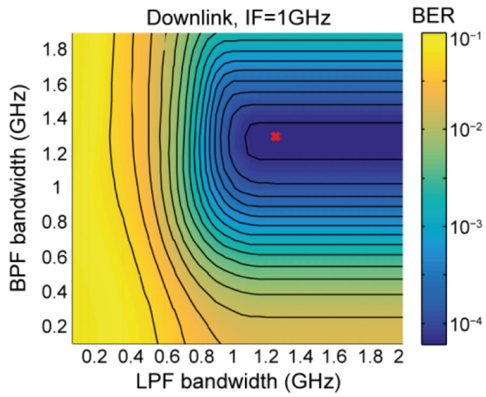

Fig. 3. Experimental results showing the optimization of digital BPF and LPF used in the Digital Receiver at the ONU (Nyquist-DPSK modulation) for 1GHz (left) and 2GHz (right) of intermediate frequency.

For the optimization of the OLT receiver (DRX_{Ui}) the BPF filter parameters have been investigated while the LPF bandwidth has been fixed to the same value than in the ONU Digital Receiver, 1.25GHz. Two BPF main parameters, the bandwidth and the low cut-off frequency, have been optimized to reduce the BER for the same two heterodyne IF frequencies (1GHz and 2GHz) at the same conditions of −48dBm NRZ-DPSK uplink signal at the receiver. As shown in Fig. 4, the optimum lower cut-off frequencies are 0.6GHz (IF = 1GHz) and 1.2GHz (IF = 2GHz), respectively. These optimum cut-off frequencies eliminate part of the main spectral lobe of the NRZ-DPSK signal (30% for IF = 1GHz and 10% for IF = 2GHz, respectively) but also remove almost completely the non-heterodyned signal, which can be greater than the useful signal, and scales up as the number of udWDM channels increases. The optimum BPF bandwidths are 1.6GHz and 2.3GHz, for 1GHz and 2GHz intermediate frequency respectively.

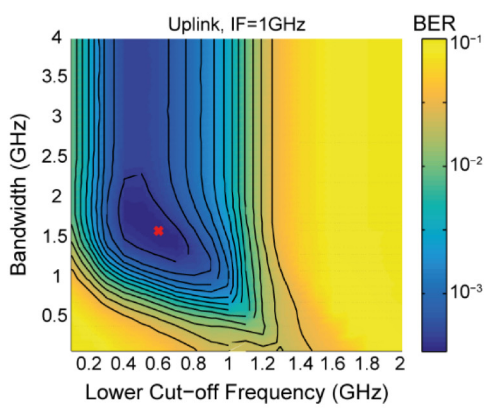

Fig. 4. Experimental results showing the optimization of digital BPF used in the Digital Receiver at the OLT (NRZ-DPSK modulation) for 1GHz (left) and 2GHz (right) of intermediate frequency.

#252375 Received 20 Oct 2015; revised 21 Dec 2015; accepted 22 Dec 2015; published 7 Jan 2016

3. Results

The performance of both links, downlink with Nyquist-DPSK modulation over MZM and uplink with NRZ-DPSK directly-modulated DFB, has been analyzed to proof the feasibility of the proposed flexible udWDM full-duplex optical link. The first analyzed parameter is the sensitivity of each link, which is defined as the minimum received power to ensure a minimum quality of the links. The second analysis focuses in the spectral separation of the uplink and downlink wavelengths, which determines their allocation inside the frequency slot. Both analyses have been performed for two IF heterodyne frequencies (1GHz and 2GHz).

3.1 Sensitivity

The sensitivity of both links has been defined as the minimum received power to ensure a 10^{-12} BER using a 7% overhead FEC, as recommended by ITU-T G.975.1 [12]. This FEC limit requires a maximum received BER of $2.2 \cdot 10^{-3}$.

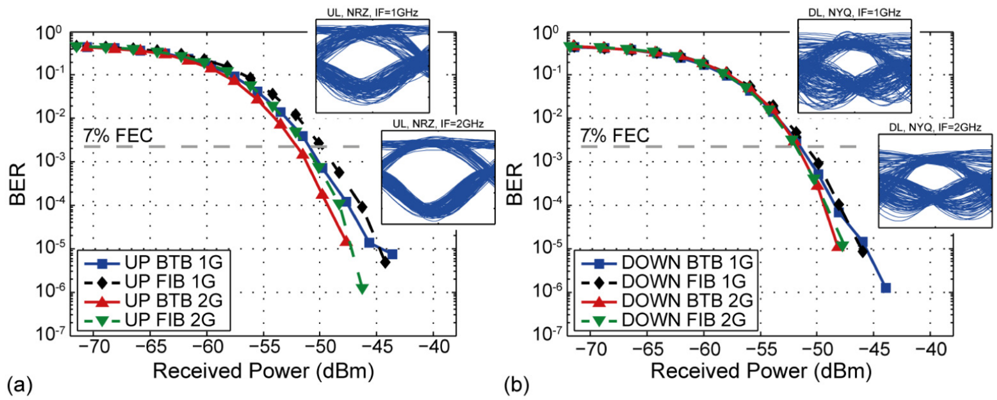

Fig. 5. BER versus received power for the two links in the OLT-ONU connection, uplink (left) and downlink (right), and for the two heterodyne frequencies (1GHz and 2GHz). Inlets: Eye diagrams for $P_{RX} = -36$dBm.

The back-to-back (BTB) downlink sensitivity is −52dBm with a heterodyne frequency of 2GHz, as shown in Fig. 5(b), and the sensitivity penalty when reducing the heterodyne frequency down to 1GHz is lower than 0.5dB. The interference of the non-heterodyned part of the received signal, affecting more significantly as commented before, generates this power penalty. The downlink is almost unaffected by the fiber transmission, as the power penalty of a transmission through 50km of ITU-T G.652.A SSMF [13] is below 0.5dB. This small dispersion power penalty is due to the narrow bandwidth of the Nyquist-DPSK modulation, around 1GHz for a 1Gbps data rate.

The BTB uplink sensitivity, as shown in Fig. 5(a), is the same than in the downlink (−52dBm) using a heterodyne IF of 2GHz and −51dBm when the heterodyne IF is 1GHz. The power penalty for reducing the intermediate frequency is 1dB because the optimized digital filters remove a greater part of the signal spectrum when the heterodyne IF is 1GHz than when it is 2GHz. The power penalty of 50km ITU-T G.652.A SSMF at the uplink is slightly higher than 1dB due to the wider spectrum transmitted through the NRZ-DPSK modulation.

3.2 Link separation / Frequency slot composition

The user channel is composed of two streams, downlink and uplink, which allocation inside the frequency slot has to ensure a null BER penalty due to the transmission Rayleigh backscattering in the receiver, e.g. the OLT transmitter should not affect the OLT receiver. This is usually avoided by separating the up and down wavelengths, but in our case we are trying to set them as close as possible following a udWDM scheme, so it is important to

#252375 Received 20 Oct 2015; revised 21 Dec 2015; accepted 22 Dec 2015; published 7 Jan 2016

analyze this point. Moreover, the frequency slot composition is the same for all the users, so a downlink stream will be always between two uplinks and vice versa, see Fig. 1. Thus, the distribution of the links inside a frequency slot has also to ensure that the interference of the transmission Rayleigh backscattering of a stream does not introduce a BER penalty in its two adjacent streams.

The analysis of the BER penalty introduced by a transmitting link over its own receiver and the adjacent one has been studied for two different transmitter optical powers (0dBm and −6dBm). This analysis has been done using the most critical configuration for the backscattering of each link, placing a 50km-long SSMF spool in different locations, as shown in Fig. 6. This fiber is long enough to generate a maximum level of Rayleigh backscattering optical power, which is practically constant for optical fibers longer than 20 km [14]. The LO used in the receivers has been shifted down from the central frequency of the received link at two heterodyne IF 1GHz and 2GHz. As it is shown in Fig. 6, adjacent links are varied −8GHz to 6GHz from the central frequency of the 1Gbps link under BER analysis.

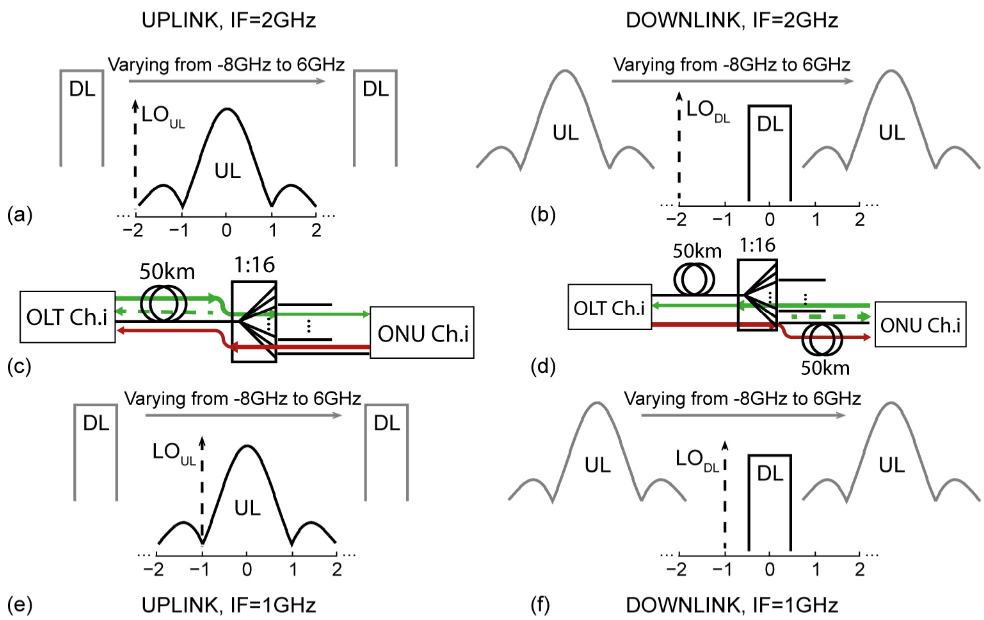

Fig. 6. Link separation setup (c, d), position of the received links and LOs and variation of the interference-backscattering link (a, b, e, f).

For the uplink characterization, the OLT is, simultaneously, receiving a −48dBm uplink transmitted by the ONU of the user channel Ch.i and transmitting the downlink of the same user channel Ch.i or of the adjacent user channel Ch.i ± 1. The worst network-configuration for this case, which is also the most common, is that one where a long feeder fiber (50km) is placed between the OLT and the 16-splitter (1:16), because the generated backscattering by the downlink will not be attenuated by the splitter, see Fig. 6(c). As shown in Fig. 7(a), there is a clear BER penalty when the + 0dBm downlink is placed in the frequency band between −6GHz and + 2GHz (8GHz) from the central frequency of the uplink. This frequency band must be avoided for the downlink. If the optical power transmitted by the downlink is reduced, both, BER penalty and banned frequency-band, are reduced (as shown in Table 1, where all the configurations are summarized). In fact, when the downlink optical transmitted power is −6dBm, it can be placed over this of the LO (at −2GHz) because the BER penalty is practically null. This special band is due to the narrow spectral bandwidth of the Nyquist-DPSK transmission used in the downlink (1GHz) and the optimal lower cut-off frequency of

#252375 Received 20 Oct 2015; revised 21 Dec 2015; accepted 22 Dec 2015; published 7 Jan 2016

the BPF for IF 2GHz (1.2GHz as commented previously), therefore effectively filtering out any Rayleigh backscattering interference. This reduction in the BER at the spacing of the LO wavelength decreases significantly, when the heterodyne frequency is 1GHz, see Fig. 7(c). In this case, the optimum lower cut-off frequency of the BPF for IF 1GHz of 0.6GHz does not filter out completely the Rayleigh backscattering interference of the Nyquist-DPSK downlink. In this case, the optimum lower cut-off frequency of the BPF for IF 1GHz of 0.6GHz does not filter out completely the Rayleigh backscattering interference of the Nyquist-DPSK downlink. Fortunately, the banned frequency band is also reduced, from −4GHz to + 2GHz (6GHz).

For the downlink characterization, the ONU is receiving a −48dBm downlink signal transmitted by the OLT while it is transmitting the uplink of the same user channel Ch.i. The worst network-configuration is that one presenting a long drop SSMF (50km) between the 16-splitter (1:16) and the ONU, as depicted in Fig. 6(d), significantly longer that typical PON deployments, hence covering worst conditions. In this case, the banned-band is higher than in the uplink case, between −6GHz and + 4GHz (10GHz) from the central frequency with a + 0dBm uplink, see Table 1, and the LO is placed at −2GHz position, see Fig. 7(b). Even more important is that now there is not a non-banned frequency band around the LO when the IF is 2GHz, where a clear reduction in the BER values can be seen although it is not enough. The reduction of the banned frequency band when the heterodyne frequency is 1GHz, see Fig. 7(d), also happens in the downlink case. The reason is that the Rayleigh backscattering interference signal, proportional to the spectrum of the uplink NRZ-DPSK directly-modulated DFB is significantly broader. Therefore, the BPF cannot properly filter out the inference signal, neither for IF = 2GHz, nor for IF = 1GHz. The case of the interference of the uplink of the adjacent ONU (Ch.i-1) has been tested but it is not shown because the interference with the interest ONU is null for both 0 and −6dBm optical powers. For clarifying, the uplink of the adjacent ONU (Ch.i-1) is attenuated by the 1:16 splitter and the Rayleigh backscattering generated at the 50Km feeder fiber is also attenuated again by the 1:16 splitter. Summarizing the Rayleigh backscattering arriving to ONU (Ch.i) due to uplink of the adjacent ONU (Ch.i-1) is fully negligible as it has been checked experimentally.

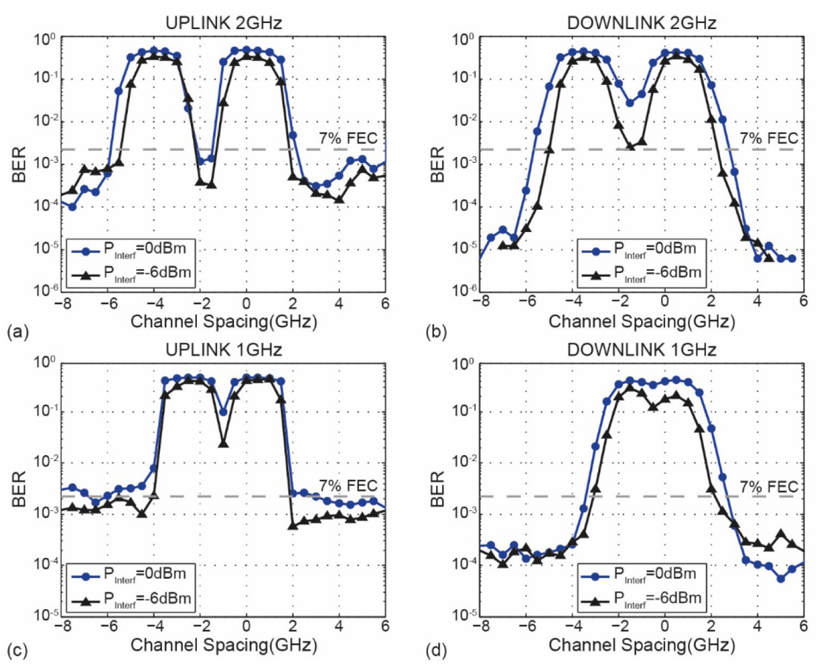

Fig. 7. BER penalty for different links: ONU downlink (a, c) and OLT uplink (b, d).

#252375 Received 20 Oct 2015; revised 21 Dec 2015; accepted 22 Dec 2015; published 7 Jan 2016

In both links, the optical power reduction of the transmitted interference signal leads to a reduction of the banned frequency bands due to the reduction of the backscattering power, including the generated by the secondary lobs of the NRZ-BPSK.

Table 1. Banned frequency bands for the adjacent links. Referenced to the received signal central frequency.

Interference Transmitted Power	Downlink IF = 1GHz	Downlink IF = 2GHz	Uplink IF = 1GHz	Uplink IF = 2GHz
0dBm	−4GHz to 3.5GHz	−6GHz to 4GHz	−4GHz to 2GHz	−6GHz to 2GHz
−6dBm	−3.5GHz to 3.5GHz	−6GHz to 3.5GHz	−4GHz to 2GHz	−6GHz to −2.5GHz −1.5GHz to 2GHz

4. Discussion: channel distribution and power budget

Based on the previous analysis, it is possible to allocate the two links of each user channel in a 6.25GHz frequency slot for the two heterodyne frequencies used in this study, as shown in Fig. 8. In both cases, the transmitted optical power for all the links is fixed to −6dBm in order to obtain a channel allocation without BER penalties.

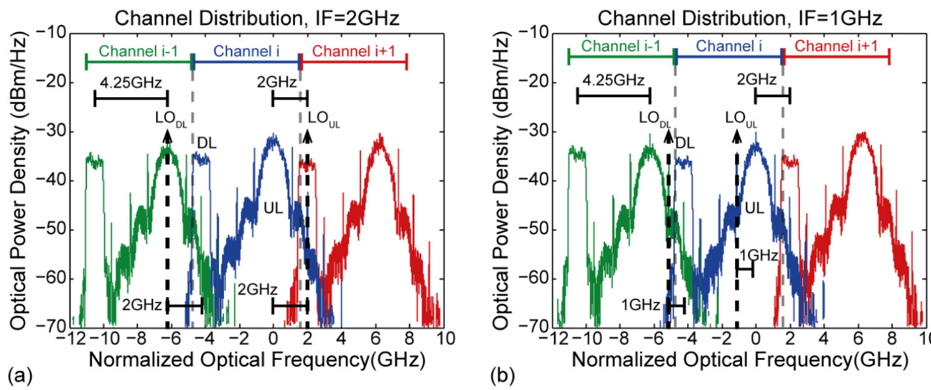

Fig. 8. Spectrum of three contiguous OLT-ONU channels. The central frequency corresponds to 1560.3nm.

When the heterodyne frequency is 2GHz, Fig. 8(a), the separation between the central frequency of the downlink and the uplink of the same channel is 4.25GHz. Moreover, the separation between the uplink and the downlink of adjacent channels is 2GHz. This link distribution has been done according to the channel separation results summarized at Table 1 and the non-interference between the Rayleigh backscattering of the uplink of the adjacent channel and the downlink. The LO used in the ONU is placed 2GHz below the central frequency of the downlink, while in the OLT the LO is 2GHz above the uplink central frequency, as shown in Fig. 8(a).

The channel composition, downlink and uplink position inside the frequency slot, is the same for both heterodyne intermediate frequencies. The only difference is the position of the local oscillators. As shown at Fig. 8(b), both LO are placed 1GHz below of the central frequency of their links.

Taking into account the limited transmission power for the links (−6dBm) and the sensitivity obtained in the previous section, the power budget of each link has been calculated for both heterodyne frequencies, Table 2. The best case for both links is to use a 2GHz heterodyne frequency, obtaining a power budget of 43dB for the downlink and 45dB for the uplink. This power budgets takes into account the 3dB of insertion losses of the splitter at the input of ONU and 1dB of the circulator used at the OLT, needed for separating both the

#252375 Received 20 Oct 2015; revised 21 Dec 2015; accepted 22 Dec 2015; published 7 Jan 2016

uplink and the downlink. In the 1GHz heterodyne IF case, the power budget is 42.5dB for the downlink and 44dB for the uplink. The 3dB of insertion losses of the ONU input splitter can be reduced using an asymmetrical splitter. This is possible because there is a 12dB margin between the DFB emission power and the transmitter required power at the ONU output. Thus, an 80/20 splitter can be used at the ONU where the insertion losses for the receiver will be 0.97dB in this case and the uplink would become the limiting power budget.

Table 2. Receiver sensitivity and power budget for a 16 users PON.

	IF = 2GHz		IF = 1GHz	
Link	P_{RX}	Power Budget	P_{RX}	Power Budget
Uplink	−52dBm	45dB	−51dBm	44dB
Downlink	−52dBm	43dB	−51.5dBm	42.5dB

The power budget indicates than the best case for both links is achieved for the heterodyne frequency of 2GHz and the channel distribution and the LO allocation is the Fig. 8(a). This channel allocation allows that each full-duplex channel occupies a frequency slot of 6.25GHz.

The 100GHz (200GHz) WDM channel is proposed as the basic routing unit for the metro network and as the add/drop unit channel for the metro-access interface, which will require a 1:16 (1:32) power splitter for the last distribution range. In a non-routing scenario (a standard PON without OXCs and/or ROADMs) and a 2GHz heterodyne IF frequency, the power budget (Table 2) allows maximum reach distances between the OLT and the ONU in the range of 117Km for a 100GHz WDM channel (1:16 splitter with 13.8dB insertion loss) and 103Km for a 200GHz WDM channel (1:32 splitter with 17.2dB insertion loss). In a routing scenario, the maximum reach distance will vary between 30Km to 100Km depending on the dimension (number of ROADMs and OXCs) of the metro-access network. Therefore, the number of users per WDM channel will vary depending on the bandwidth availability of the grid. For example, for a fully flexgrid, the nodes will support 16 (32) users, while in case of implementing ROADMs and OXCs based on flat top optical filters with an availability of 75% of the bandwidth, a reduced number of final users, 12 (24), will be served.

5. Conclusion

The performance of full-duplex 1Gbps optical links for a cost-effective udWDM transmission with 6.25GHz frequency slots are demonstrated and optimized for cost-effective metro-access networks. The 1Gbps downlink, transmitted by the OLT, is based on Nyquist-DPSK implemented by a MZM, and has been optimized to a transmitted power of −6dBm, providing a sensitivity of −52dBm at the ONU receiver. The uplink, transmitted by the ONU, is based on a NRZ-DPSK directly-modulated DFB providing similar transmitted power of −6dBm and a sensitivity of −52dBm at the OLT receiver. Thus, a power budget of 43dB, including the 3dB ONU splitter, is accomplished. Significant cost reduction is achieved as the OLT and ONU receivers are based on single photodiode heterodyne detection with a DFB local oscillator that can be placed at 1 or 2GHz apart from the central frequency of the link. This single photodiode heterodyne receiver can be easily upgraded with a polarization independent one.

The experimental analysis of channel separation demonstrates the allocation of full-duplex 1Gbps optical links inside 6.25GHz frequency slots preserving the 43dB power budget by optimized channel spacing allocation. This allocation permits: 16 (32) users to be served for each 100GHz (200GHz) fully flexgrid WDM channel, in ranges of more than 100Km considering commercially available power splitter insertion losses; and coexistence at shorter reaches with future mesh 5G metro-access networks including ROADMs and OXCs.

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