Bidirectional symmetric 8×10.7Gb/s WDM-PON over 108 km installed fiber using low complexity polarization-insensitive coherent ONUs

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Abstract *Polarization-time block-coded OFDM-QPSK downstream channels are robustly detected using a polarization-insensitive coherent receiver, consisting of only a 3dB coupler and single balanced PD. 8×10.7Gb/s channels are bidirectionally transmitted over 108 km installed fiber achieving a 1:16-way passive split.*

Introduction

The standardized NG-PON2 specifications, requiring at least 40 Gb/s aggregate data rate, permit wavelength division multiplexing (WDM) for passive optical networks (PONs)[1]. Previously demonstrated solutions have achieved impressive aggregate data rates and transmission distances using a λ-selective ONU transceiver and optical extender[2]. However, considering the continuous growth in bandwidth demand per subscriber, i.e., the increase in the number of connected devices per subscriber and bandwidth-hungry applications per device, it is desirable to have uncontented gigabit-capable connections per subscriber, where coherent WDM PONs can play an important role.

Digital coherent modulation and detection offer many advantages for PON applications: robustness to chromatic dispersion providing long reach transmission distance, exceptionally high receiver sensitivity leading to high number of subscribers in a network (consequently, potentially reducing the operational cost per subscribers), and inherent frequency selectivity for colorless network operation (no need for array waveguide grating in the ONU)[3]. However, the high optical complexity required for a phase- and polarization-diverse intradyne receiver (two polarization beam splitters (PBSs) followed by an 8-port optical hybrid and 4 balanced photodiodes each of which requires an analogue to digital converter (ADC)) is unfavorable for such low cost applications. Rohde *et al.*[4] proposed heterodyne receivers for PONs, in which an optical hybrid is replaced by a 3-dB coupler and the required number of photodiodes and ADCs is halved. However, this solution still requires a PBS. Although the monolithic integration of such receivers is possible, it is challenging using mature manufacturing techniques. To overcome this limitation, we have recently demonstrated a polarization-insensitive coherent receiver, that is implemented using an Alamouti-coded optical orthogonal frequency division multiplexing (AC-OFDM) signal combined with heterodyne reception. Such technique removes the PBS requirement, and further, reduces the receiver optical components down to a single balanced photodiode and a local oscillator (LO) laser[5]; comparable to an intensity modulation-direct detection (IM-DD) transceiver. In addition, only a single high speed ADC is required.

Here, for the first time, we present a bidirectional symmetric 8×10.7 Gb/s transmission over 38.8 and 108 km using a low complexity coherent ONU without mid-span amplification or opto-electronic reach extenders; demonstrating the chromatic dispersion tolerance of this technique compared with receivers of a similar optical complexity, and the exceptional power budget offered by coherent detection. To achieve polarization-insensitivity at the ONU, a pre-FEC 10.7 Gb/s AC-OFDM downstream signal was transmitted. The LO at the ONU was used both for the reception of the downstream channel and for the upstream signal transmission of 8×10.7 Gb/s BPSK signals.

Optical line terminal (OLT) and optical network unit (ONU) transceiver implementations

A. Frequency Plan

In our proposed configuration, 8 down/upstream (Ds/Us) channels were fixed to a 50 GHz frequency grid having a 12.5 GHz offset between the Ds and Us channels. Since heterodyne detection was employed in the ONU, the frequency offset between Us and Ds channels enables the simultaneous use of the LO laser for Ds channels as the source laser for Us channels. This Us/Ds frequency offset was sufficient to mitigate any penalty due to reflections in the ONU; tested up to +15 dBm reflected power using the method described in Ref.[7]. The robustness of this method to linear cross channel interference is due to the frequency selectivity of the coherent receiver used in the ONU.

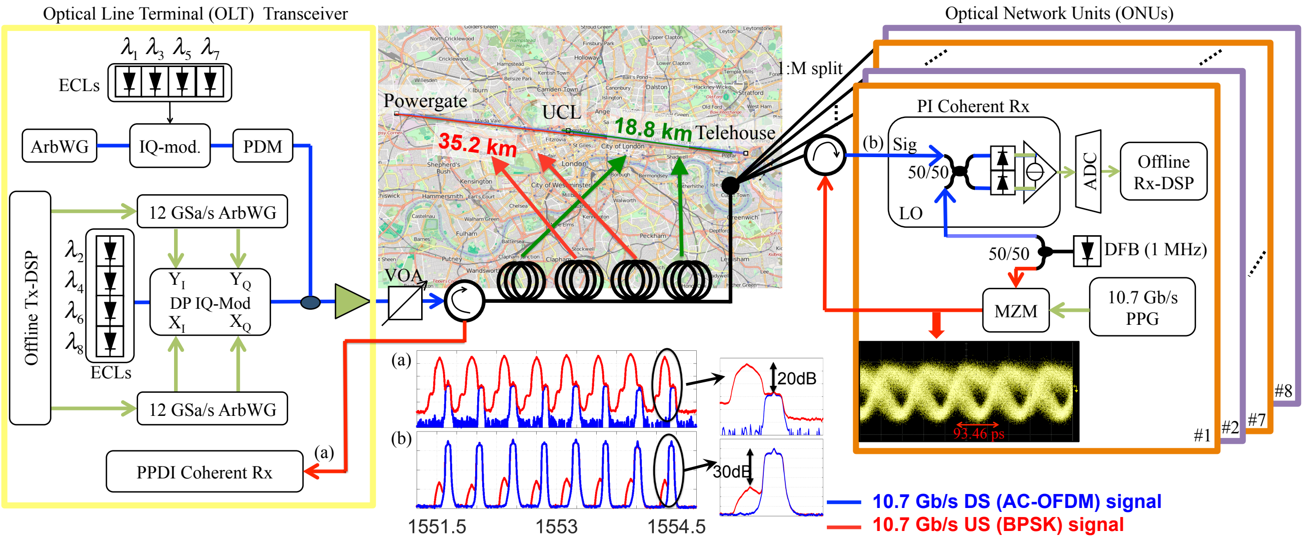

Fig. 1: Bidirectional 8×10.7 Gb/s WDM-PON test-bed. Insets: Received optical spectra in the (a) ONU, and (b) OLT. PDM: Polarization-division multiplexing emulation stage. PI Coherent Rx: Polarization-insensitive coherent receiver. PPDI Rx: Polarization- and phase-diverse intradyne coherent receiver. VOA: Variable optical attenuator. (Map inset © OpenStreetMap.)

B. Downstream (Ds) configuration

The OLT transmitter for the even channels ($\lambda_{2,4,6,8}$) consisted of a dual-polarization (DP) nested Mach-Zehnder (IQ) modulator. It was driven by using an Alamouti-coded OFDM signal, modulated with quadrature phase shift keying (QPSK) on the individual subcarriers, from an arbitrary waveform generator (ArbWG) operating at 12 GSa/s and seeded with the output from an external cavity laser (100 kHz linewidth), as described in Ref.[6]. The odd channels were generated in a similar manner using a single-polarization IQ-modulator, with the second polarization generated using a polarization multiplexing delay-line emulation stage (the output waveforms are statistically similar to AC-OFDM), as shown in Fig.1. The raw bit rate for the Ds channels was set to 11.3 Gb/s, appending 25 samples per OFDM symbol (4% overhead) as a cyclic prefix to compensate for the accumulated chromatic dispersion, and using 24 pair-wise training symbols (TSs) (20 of them at the start of the OFDM frame and 4 of them periodically - every 34 OFDM symbols) were inserted for channel estimation. This yields a total net bit rate of 10.7 Gb/s including a 7% overhead due to hard decision forward error correction (HD-FEC).

In the ONU, the Ds signal was coupled with the output from a distributed feedback (DFB) laser as a LO laser (with 1 MHz linewidth) using a 3-dB coupler, followed by a single balanced photodiode and an ADC, operating at 50 GSa/s, as shown in Fig. 1. The LO power was set to 11 dBm. The offline digital signal processing blocks for the received (Alamouti-coded OFDM) signal demodulation were applied, as reported in Ref.[5].

C. Upstream (Us) configuration

The Us signal was generated by passing the output from the local DFB in the ONU to a 3-dB power splitter, as shown in Fig.1. One output from the splitter was used as the LO laser for the downstream signal whereas the other output was used as a source for the single-drive MZM, driven by using a 10.7 Gb/s pseudo-random binary sequence, and biased to generate BPSK, as depicted in Fig.1. The bandwidth of the upstream transmitter electronics were limited to 7 GHz using a Bessel low-pass filter.

The upstream channels were detected in the OLT using a phase- and polarization-diverse intradyne (PPDI) coherent receiver and sampled with an ADC before resampling to 2 Sa/symbol digitally. The offline digital signal processing was applied as discussed in Ref.[8], but with adaptive equalization applied using an 11-tap real-valued equalizer, as described in Ref[9].

Installed fiber demonstration and loss budget evaluation

The system performance was tested first in back-to-back operation. The receiver sensitivities of -40.9 and -38.8 dBm were obtained for the Ds and Us channel #2, respectively, as shown in Fig.2.

Following this, the optical signals were transmitted bidirectionally over passive sections of a reconfigurable dark fiber network, as shown in Fig.1. Two demonstrations, that are the transmission over two and four fiber spans totaling 38.8 km and 108 km standard single mode fiber (SMF) with a combined link attenuation of 10 and 27.6 dB (0.26 dB/km), respectively, were performed. Note that the transmission over 38.8 km of SSMF commensurate with the

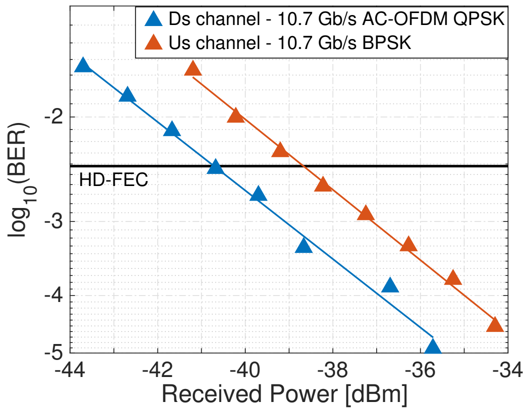

Fig. 2: BER vs. received power for channel #2 in back-to-back operation.

NG-PON2 recommendations. Although this demonstration uses a dense WDM grid of 50 GHz and an aggregate data rate of 80 Gb/s (rather than the 100 GHz and 40 Gb/s typical of NG-PON2), such measurements provide a marker for comparison with earlier demonstrations.

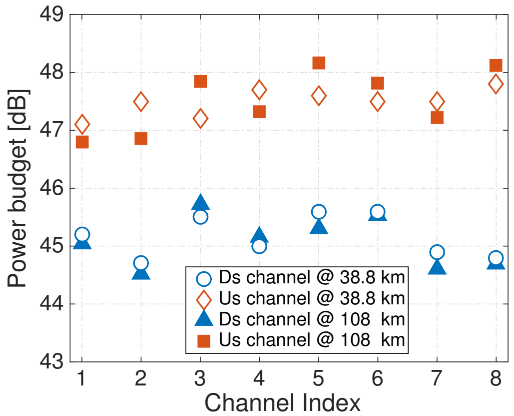

Fig. 3: Achieved power budget for all 10.7 Gb/s Ds and Us channels when transmitted over 38.8 and 108 km of installed SMF.

In both demonstrations, the Us launch power was first optimized in isolation to maximize the power budget. Following this, the Ds signal launch power was similarly optimized, but in the presence of the Us signal with its optimized launch power value. The average chromatic dispersion value for the installed fiber is 16.5 ps/nm/km. The optimum launch power for the Ds and Us channels varied $\pm$0.5 dB due to the small power variations between the channels, as can be observed from the obtained power budgets in Fig.3 and optical spectra in Fig.1 insets (a) and (b). The high power budget shown in Fig.3 (more than 44.3 dB for all channels) indicates both the achieved high receiver sensitivity using this technique, and the robustness to chromatic dispersion. Such a power budget is sufficient to enable a either 1:512-way power split after 40 km transmission (NG-PON2 compatible distance with 2.6 dB sensitivity margin) or 1:16-way power split after 108 km transmission (2.4 dB sensitivity margin). Moreover, to estimate the achievable splitting ratios with respect to the transmission distance, we extrapolated the system performance to the distances from 0 to 120 km, as shown in Fig.4. Note that the minimum achieved power budget was (=44.3 dB) used, and the loss of 1:2 power split and average fiber attenuation/km were assumed to be 3.5-dB and 0.26 dB/km, respectively in this estimation.

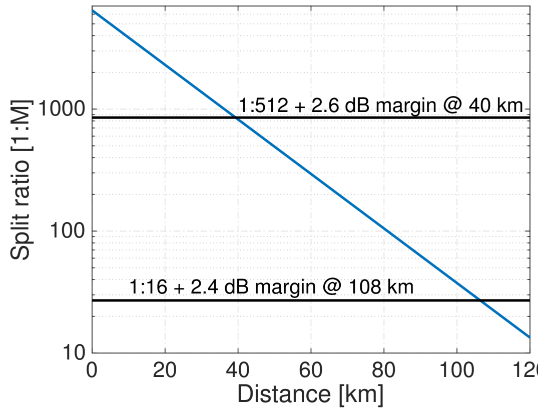

Fig. 4: Achievable split ratios for channel #2 vs distance, assuming a 3.5 dB loss/splitter and average fiber attenuation of 0.26 dB/km.

Conclusions

Bidirectional symmetric transmission of 8$\times$10.7 Gb/s WDM signals using a simplified cost effective coherent ONU over installed fiber PON links has been demonstrated. At the transmission distances of 38.8 and 108 km of SSMF, a power budget of 44 dB was achieved for all 8 channels allowing for 1:512 and 1:16 way passive split, respectively.

Acknowledgments

This work was supported by the EPSRC UNLOC EP/J017582/1, and EP/J008842/1. The authors also wish to acknowledge the EPSRC National Dark Fiber Infrastructure Service, NS/A000021/1 for providing access to the Aurora2 dark fiber network.

References

[1] ITU-T recommendation G.989.1, “40-Gigabit-capable passive optical networks (NG-PON2): General requirements” (2013).

[2] K. Taguchi *et. al.*, “First field trial of 40-km reach and 1024-split symmetric-rate 40-Gbit/s λ-tunable WDM/TDM-PON,” Proc. OFC, PDP Th5A.5 (2015).

[3] D. Lavery *et al.*, “A long-reach ultra-dense 10 Gbit/s WDM-PON using a digital coherent receiver,” Opt. Express, Vol. 18, no. 25, p. 25855 (2010).

[4] H. Rohde *et al.*, “Next generation optical access: 1 Gbit/s for everyone,” Proc. ECOC, 10.5.5 (2009).

[5] M.S. Erkılınç *et al.*, “Polarization-insensitive single-balanced photodiode coherent receiver for long-reach WDM-PONs,” J. Lightw. Technol., Vol. 34, no. 8, p. 2034 (2016).

[6] M.S. Erkılınç *et al.*, “Polarization-insensitive single balanced photodiode coherent receiver for passive optical networks,” in Proc. ECOC, Th.1.3.3 (2015).

[7] D. Lavery *et al.*, “On the impact of backreflections in a bidirectional 10 Gbit/s coherent WDM-PON,” Proc. OFC, OTh1F.3 (2012).

[8] R. Maher *et al.*, “Fast wavelength switching 6 GBd dual polarisation 16QAM digital coherent burst mode receiver,” IEEE Photon. Technol. Lett., Vol. 26, no. 3, p.297 (2014).

[9] M. Paskov *et al.*, “Blind equalization of receiver in-phase/quadrature skew in the presence of Nyquist filtering,” IEEE Photon. Technol. Lett., Vol. 25, no. 24, p. 2446 (2013).