A long-reach ultra-dense 10 Gbit/s WDM-PON using a digital coherent receiver

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Abstract: We investigate the impact of channel spacing and nonlinear transmission over 120 km of standard single mode fiber for a 10 Gbit/s long-reach wavelength division multiplexed passive optical network (WDM-PON). We employed polarization division multiplexed quadrature phase shift keying (PDM-QPSK), which allowed data transmission at 3.125 GBaud, including a 25% overhead for forward error correction. To receive this spectrally efficient modulation format, a digital coherent receiver was employed, allowing for both frequency selectivity and an increased sensitivity of -45 dBm (25 photons/bit). We investigated a channel spacing as low as 5 GHz, for which the loss budget was 48.6 dB, increasing to 54.0 dB for a 50 GHz grid.

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1. Introduction

Digital coherent receivers have caused a revolution in the design of core networks, however, they have the potential to be equally disruptive in the access network, albeit for different reasons. Here, it is the frequency selectivity and high receiver sensitivity afforded by coherent detection which will be exploited, enabling ultra-dense wavelength division multiplexed (UDWDM) long-reach passive optical networks (LR-PON) to be realized. In contrast to a conventional LR-PON [1], the proposed approach does not require midspan transponders or erbium doped fiber amplifiers (EDFA) to implement a 100 km access network with 1024 subscribers, thereby allowing for a true passive optical network. As such, this network architecture delivers real estate and maintenance savings through the elimination of the metro network and associated equipment. While the cost of a digital coherent receiver will be higher than a conventional receiver, over the lifetime of the system this will be outweighed by the reduced operational costs per subscriber due to the increased network capacity afforded by UDWDM, allowing multiple subscribers to share a single fiber.

Early research into optical access networks utilized coherent receivers for their frequency selectivity [2,3] (although the resurgence of the technology has been largely due to improvements in digital signal processing (DSP) [4]). Coherent receivers act as narrow optical bandpass filters when tuned to the required channel frequency [5] and, therefore, obviate the need for optical filtering, which would be required for direct detection receivers. This intrinsic property of coherent receivers is especially advantageous in an access network, as channel switching is made possible simply through re-tuning the local oscillator (LO) laser.

Recent investigations using coherent receivers in WDM-PONs have generally involved low baud rate transmission with heterodyne or self-homodyne detection [6–9]. To date, investigations into 10 Gb/s WDM-PONs have not yielded sufficient receiver sensitivity to implement the LR-PON [10]. Our investigation has focused on the downstream portion of the network in order to directly assess receiver sensitivity. We believe this is the first time that the LR-PON operating at 10 Gbit/s has been demonstrated, in any form, without the use of midspan repeaters.

2. Proposed LR-PON Design and Experimental Configuration

Our proposed implementation of the downstream LR-PON link uses an optical line terminal (OLT) transmitting a dense wavelength division- and polarization division-multiplexed quadrature phase shift keyed (WDM-PDM-QPSK) optical signal modulated at 3.125 GBaud. This modulation format carries 4 bits/symbol, which corresponds to a transmission rate per channel of 10 Gb/s with a 25% coding overhead, such as that demonstrated by Mizuochi [11], which allows bit error rates (BER) up to 2×10^{-2} to be corrected to below 10^{-15}. An EDFA at the transmitter sets the power sent to the fiber backhaul, and passive optical splitters and a shorter span of fiber are used to distribute the signal to the optical network units (ONU). We propose the use of a coherent receiver in each ONU to improve receiver sensitivity and provide channel

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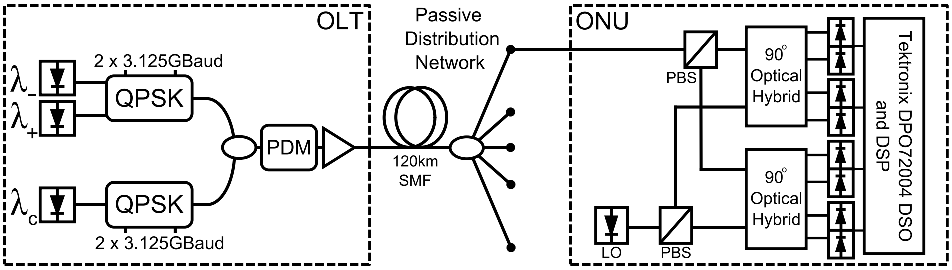

Fig. 1. LR-PON Experimental configuration, where the power loss due to the splitting in the Passive Distribution Network is emulated by a variable optical attenuator. Note that, in practice, multiple channels created at the OLT could be generated using a single laser with subcarrier multiplexing [12], or through time-domain modulation of wavelength-swept light [13].

selectivity through the use of a tunable LO laser source.

The maximum number of subscribers to the LR-PON, and the maximum transmission distance, can be specified by the loss budget; the sum of all losses incurred between the OLT and an ONU. In the experimental case, this is the sum of the total span attenuation (typically 0.2 dB/km) and the attenuation applied at the receiver. In a deployed system, attenuation is incurred from the fiber backhaul and access spans, and through passive splitting; the minimum attenuation due to splitting is $\log_{10}(\mathrm{SR})$ dB, where SR is the split ratio. Notionally, the minimum required split ratio of 1:1024 is achievable with a loss budget of approximately 30 dB plus the total span attenuation.

To model the LR-PON experimentally (Fig. 1), we multiplexed CW light from three external cavity lasers (ECL); applying QPSK modulation to the outer (λ_- and λ_+) and central (λ_c) channels separately. The applied pattern was a pseudo-random bit sequence (PRBS) of length $2^{15}-1$. Polarization multiplexing was acheived by adjusting signal polarization states in each arm of a passive delay-line stage. The launch power to the span was set by an EDFA followed by a variable optical attenuator (VOA). The span consisted of 120 km of standard single-mode fiber (SMF) to model the access and backhaul spans. At the receiver, a VOA was used to emulate the power loss due to the passive optical splitters. The signal was detected with a phase and polarization diverse coherent receiver, and digitized by a digital sampling oscilliscope (DSO). The output from the DSO was resampled to 6.25 Gsamples/s to give 2 samples/symbol, and at least 2^{16} symbols (2^{17} symbols for BER less than 10^{-4}) were then used to recover the constellation offline using DSP in Matlab, as in [14]. (Note that, due to the short spans involved, dispersion compensation was omitted.)

The LO laser was provided by a fourth ECL, amplified to 13 dBm via an EDFA and tuned to λ_c. The frequency offset between the signal and LO lasers was measured as less than 0.1 GHz. Optical channel powers were measured using calibrated optical spectrum analyzers (OSA) at the transmitter and receiver.

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3. Experimental Results and Discussion

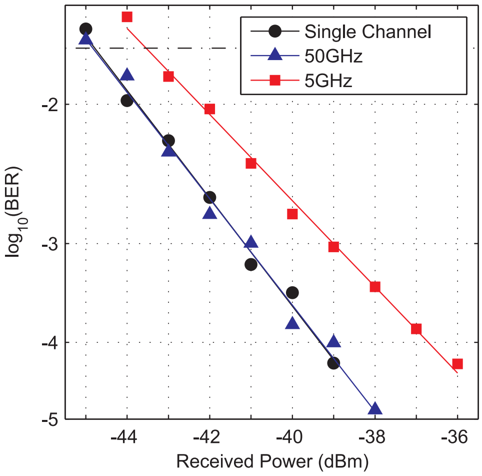

Fig. 2. Back-to-back sensitivity measurements at different channel spacings. At the 2×10^{-2} FEC limit (dashed line), the sensitivity penalty is 1.3 dB for a 5 GHz channel spacing.

In these investigations, we have sought to determine the sensitivity of a digital coherent receiver, and evaluate its prospective performance when used in a WDM-PON. To achieve this, experiments were undertaken to evaluate the performance of single channel and 3-channel WDM back-to-back and transmission over 120 km of SMF.

Fig. 2 shows the impact of channel spacing on the back-to-back receiver sensitivity. There is no observed penalty between single channel and 50 GHz spaced channels, but reducing the channel spacing to 5 GHz incurs a 1.3 dB penalty at the 2×10^{-2} BER. We attribute this penalty to the introduction of coherent crosstalk and in-band noise. In comparison with previous investigations employing coherent detection, this configuration represents a significant improvement with a receiver sensitivity of -45 dBm (25 photons/bit). This high sensitivity is due to the use of PDM-QPSK with a digital coherent receiver, which includes an adaptive digital equalizer and a high FEC overhead. This sensitivity is compared with published results in Table 1.

Note that, as the receiver sensitivity approaches the shot noise limit, preamplification of the signal (using an EDFA, for example) can further reduce the required received power [15]. It is unfeasible for each ONU to utilize an EDFA for this purpose due to the increased cost per unit. However, a single EDFA could be used to preamplify all channels prior to the OLT for upstream transmission; this is a subject for further investigation.

Table 1. **Reported receiver sensitivities for coherent PON experiments**

Paper	Bitrate (Gbit/s)	Modulation Format	bits/symbol	photons/bit*
These Results	12.5	PDM-QPSK	4	25
Jung [8]	1.25	BPSK	1	33
Narikawa [6]	1.25	ASK	1	100
Kim [10]	10.0	QPSK	2	155

* Assumes 25% coding overhead. Sensitivities are for a BER of 2×10^{-2} extrapolated from the reported results.

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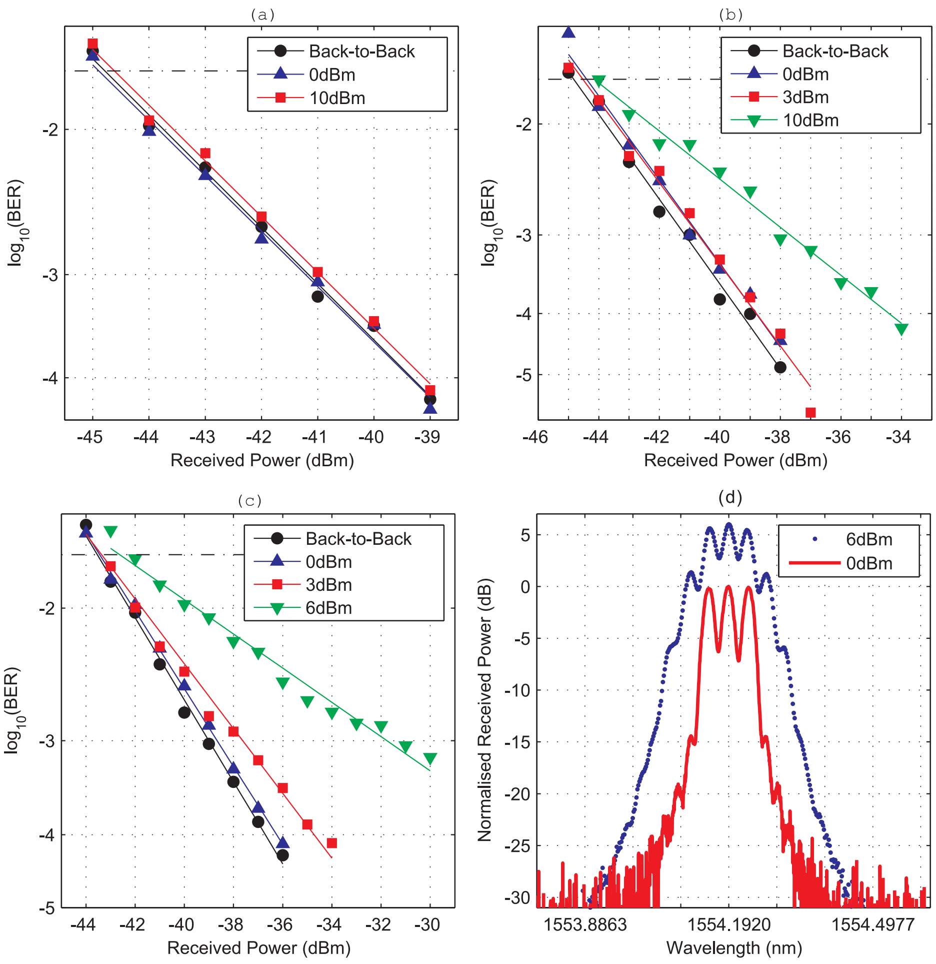

Fig. 3. Back-to-back and transmission at different launch powers for (a) single channel (b) 50 GHz channel spacing (c) 5 GHz channel spacing. The 2×10^{-2} FEC limit is indicated by the dashed line. For a 5 GHz grid, the loss budget is 48.6 dB, increasing to 54.0 dB for a 50 GHz grid. The received spectrum for 5 GHz channel spacing after 120 km SMF is shown in (d). For a 6 dBm launch power, four-wave mixing (FWM) effects become visible. Note that, for high launch powers, the BER performance of the central channel is degraded with respect to the outer channels, which we attribute to the central channel being impaired by cross phase modulation (XPM) and FWM products from both outer channels.

The transmission experiments investigated the impact of nonlinearities on sensitivity. Fig. 3(a) shows that for single channel transmission over 120 km, with a launch power of up to 10 dBm, the incurred penalty is less than 0.3 dB. Thus, the impact of self phase modulation (SPM) is negligible for the launch powers considered herein. Fig. 3(d) shows the received spectrum for 5 GHz spaced channels at 6 dBm and 0 dBm launch powers. For the higher launch powers, FWM products are clearly visible, and this is reflected in the observed penalty.

It is clear from Fig. 3(b) and Fig. 3(c) that, in the FEC region of interest, 2×10^{-2}, the impact of nonlinearities on the BER is reduced. We observed a nonlinear penalty of less than 1 dB at launch powers of 6 dBm and 10 dBm per channel for 5 GHz and 50 GHz channel

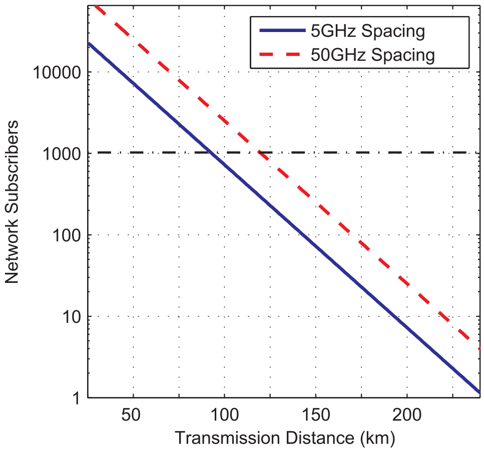

Fig. 4. Split ratio vs. maximum transmission distance. Dashed line shows 1:1024 split ratio.

spacings, respectively. As such, the overall penalty for high launch powers is reasonably low. Fig. 3(b) shows that for a 50 GHz spacing and a 10 dBm launch power, the loss budget is 54 dB; corresponding to a maximum transmission distance of 120 km followed by a 1:1024 split. For the shorter, 100 km spans considered for LR-PONs in [1], the total span attenuation is lower, and so here there is some additional sensitivity margin at the receiver.

We show in Fig. 4 the maximum split obtainable for a specified minimum transmission distance. This analysis is taken from the results in the nonlinear region (transmission powers of 6 dBm and 10 dBm for 5 GHz and 50 GHz spacings, respectively). As such, extrapolation to distances shorter than the span length are limited by the effective nonlinear length; calculated to be approximately 20 km [16]. The maximum reach for 5 GHz and 50 GHz channel spacings after a 1:1024 split was found to be 92.5 km and 120 km, respectively. However, this comparison is made for a fixed nonlinear penalty; at higher transmission powers we would expect, from the results in Fig. 3, to be able to transmit 5 GHz spaced channels over 100 km.

4. Conclusions

We experimentally determined the feasibility of an unrepeated LR-PON operating at 10 Gb/s per wavelength, by transmitting 3-channel WDM-PDM-QPSK at 3.125 GBaud over 120 km. The 25% transmission overhead was reserved for strong FEC. Sensitivity gains were due largely to the digital coherent receiver. The loss budget was maximized at 54.0 dB by using a 50 GHz channel spacing and a 10 dBm launch power; corresponding to 120 km transmission followed by a 1:1024 split. We found the nonlinear penalty to be least dominant in the high BER region such that there is a greater margin for high transmission powers when using strong FEC. This is the first time that the downstream link of an LR-PON operating at 10 Gbit/s per wavelength has been demonstrated without midspan repeaters.

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