100-Gb/s Point-to-point Solutions for Long-reach Passive Optical Networks in Sparse Rural and Urban Areas

Elias Giacoumidis[1,2], **Giuseppe Talli**[3], **Naoise Mac Suibhne**[1], **Son T. Le**[1], **Nick J. Doran**[1], **and David B. Payne**[1,4]

[1]Aston Institute of Photonic Technologies (AIPT), Aston University, Birmingham B4 7ET, UK
[2]Centre for Ultrahigh Bandwidth Devices for Optical Systems (CUDOS), School of Physics University of Sydney, NSW 2006, Australia
[3]Tyndall National Institute, University College Cork (UCC), Cork, Ireland
[4]Trinity College Dublin, Dublin, Ireland

Abstract— Long reach-passive optical networks (LR-PON) are being proposed as a means of enabling ubiquitous fiber-to-the-home (FTTH) by massive sharing of network resources and therefore reducing per customer costs to affordable levels. In this paper, we analyze the chain solutions for LR-PON deployment in urban and rural areas at 100-Gb/s point-to-point transmission using dual polarization-quaternary phase shift-keying (DP-QPSK) modulation. The numerical analysis shows that with appropriate finite impulse response (FIR) filter designs, 100-Gb/s transmission can be achieved with at least 512 way split and up to 160 km total distance, which is sufficient for many of the optical paths in a practical situation,for point-to-point link from one LR-PON to another LR-PON through the optical switch at the metro nodes and across a core light path through the core network without regeneration.

1. INTRODUCTION

Long reach-passive optical networks (LR-PON) are being proposed [1, 2] as a means of enabling ubiquitous FTTH by massive sharing of network resources and therefore reducing per customer costs to affordable levels. To be ubiquitous the solutions must be suitable for sparse rural areas and also must cater for very high capacity links ($\sim$ 100-Gb/s) for large business customers. The difficulty for conventional PON designs in sparse rural areas is connecting a sufficient number of customers to the PON system in order to get adequate sharing of the physical infrastructure and therefore achieve a low cost per customer. A further problem is the longer distances between splitter nodes and customers, which requires longer cable lengths with higher fibre count which also increases cost per customer. Also the size of small rural communities can be much less than the total LR-PON split which would mean that the conventional "lollipop" design [2], with long feeder and large split within a relatively small fibre reach < 10 km, can be underutilised which directly increases the cost per customer.

In this paper, we consider the use of "chained" cable and amplifier solutions to improve LR-PON utilisation in rural areas as shown in Fig. 1. The amplifier nodes for a single LR-PON are shown in a chain configuration with 4 fibres required between the amplifier nodes for each LR-PON chain while only 2 fibres are required from the primary and secondary metro-nodes to the closest respective amplifier nodes. This solution shares one optical line terminal (OLT) working and one protection OLT for all the amplifier nodes in the chain, it maintains full wavelength availability at all amplifier nodes and also works for single wavelength entry solutions. The cost penalty compared to the "lollipop" model is the greater number of amplifiers per customer due to the smaller split (and hence smaller number of customers) at each amplifier node. The feeder fibre and inter node fibres remain highly shared as with the urban "lollipop" model and should not add significantly to the cost per customer.

Although protection switching is more complex than for the simple "lollipop" LR-PON model used for dense areas due to the increased number of failure modes that can occur full protection can still be achieved. The only additional issue is that the upstream amplifiers in the secondary path need to be off to avoided multipath propagation and an amplified loop: An example of such a loop is shown by the path highlighted in red in Fig. 1. Note also that the centre amplifier nodes in the chain requires 4×8 splitters to provide the chain ports to connect to their adjacent amplifier nodes; the edge amplifier nodes only require 4×4 splitters as in the usual "lollipop" LR-PON configuration. The need to turn-off the amplifiers in the protection path (to avoid the risk of amplified loops) reduces "fault coverage" because the protection path cannot pass light unless the amplifiers are bypassed with an out-of-band wavelength. The chain cable concept can also be

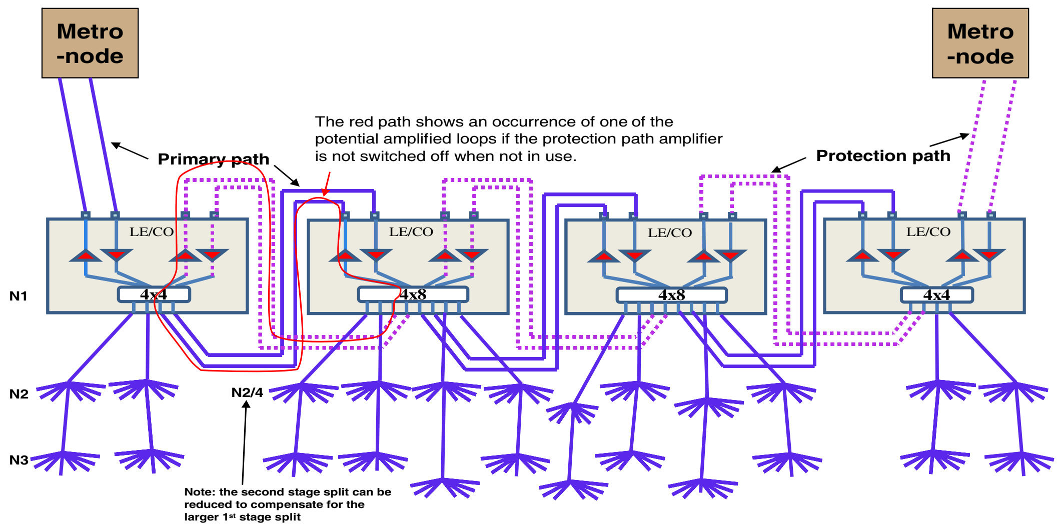


Figure 1: Chain configure if distributed amplifier structure.

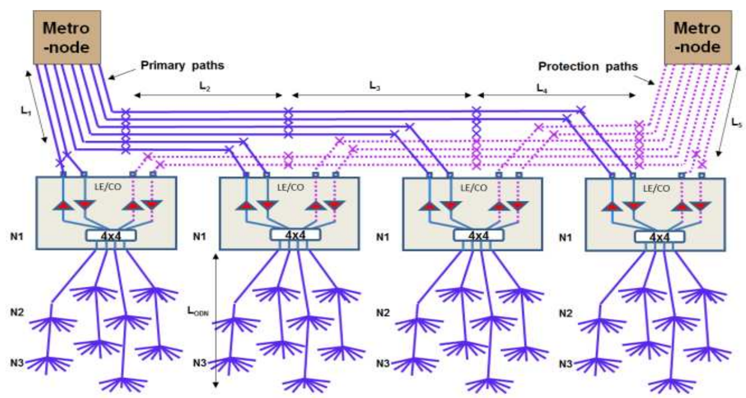


Figure 2: Chain cable model applied to LR-PON "lollipop" model for urban areas.

applied to the "lollipop" LR-PON model in urban areas as shown in Fig. 2. This configure applies to denser ares where each local exchange (LE) site/central office (CO) serves sufficient customers for at least one LR-PON and could contain amplifiers for several LR-PONs. For both rural and urban solutions (Figs. 1–2) the cable chain is configured between a pair of adjacent metro-nodes, the number of LE/CO sites in the chain would depend on local customer densities and LE/CO site densities. The number of fibres in the cable serving the chain is equal to 2 times the total number of LR-PONs (for the urban "lollipop" case) in all the LE/CO sites connected via the chain cable plus any spare fibre planned for future growth. This makes very efficient use of the feeder cable fibre network and minimizes cost per customer.

2. 100 G-DP-QPSK TRANSMISSION OVER LR-PON INFRASTRUCTURE

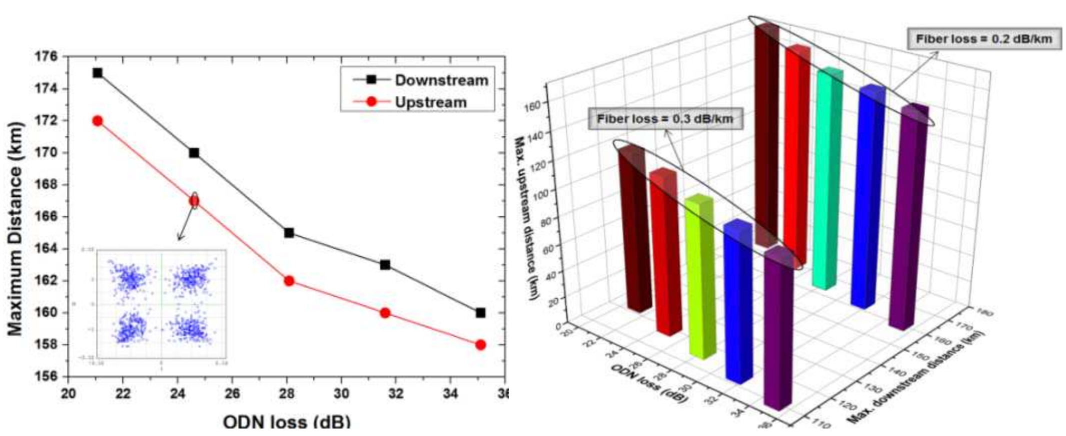
The basic 10-Gb/s LR-PON proposal [2] assumes 10-Gb/s symmetrical OOK transmission system carrying a hybrid DWDM/TDMA protocol with dynamic bandwidth allocation (DBA) and dynamic wavelength allocation (DWA). A 40-Gb/s bit interleaved downstream system as a future upgrade of the LR-PON capacity is also being considered [3]. However although there will be spare fibres in the LR-PON cable for a limited number of bespoke fibre networks for some customers we also need a 100-Gb/s point-to-point solution that operates over wavelengths in the DWDM multiplex operating over the LR-PON infrastructure. Such a solution can enable ubiquitous access to the core network and provide 100-Gb/s private circuits on either a static or via dynamic SDN basis. Dual-polarization quaternary phase-shift keying (DP-QPSK) at 25-GBaud symbol rate is a good candidate for the implementation of next generation high-speed transmission systems [4]. It helps to reduce the requirements on electrical and opto-electrical components because it requires a symbol-rate of only $\frac{1}{4}$ of the bit-rate. In addition, digital signal processing (DSP) combined with coherent detection has the potential to mitigate the impact of transmission impairments. In particular, coherent DP-QPSK uses a DSP unit which is able to mitigate the impact of phase noise (phase and frequency mismatch between laser transmitter and local oscillator [LO]), chromatic dispersion (CD) and polarization-induced distortions, i.e. polarization mode dispersion (PMD) and polarization cross-talk (cross-talk between orthogonally polarized channels resulting from the misalignment between the states of polarization [SOP] of the LO and the detected signal using polarisation beam splitters [PBSs] in signal and LO paths).

Our simulation setup consists of a single-channel using a combination of two 50-Gb/s DP-QPSK transmitters resulting in total 100-Gb/s (25-GBaud), a transmission line and polarization-diversity receivers that include two 90° hybrids and a DSP unit (downstream PON). The noise figure of the optical amplifier (an Erbium-doped fiber amplifier [EDFA]) was set at 5.5 dB. PIN photodiodes have been used for the coherent homodyne receiver and the laser and LO linewidth have been set to 1 MHz. Finally the optical and electrical band-pass filters (OBPF) are of 1st order with Gaussian transfer function and 100 GHz bandwidth, whilst the filter in the ONU is Bessel type. The transmission line is composed of a standard single-mode fiber (SSMF) and a polarization tracker (to control the alignment between the signal SOP and the PBS at the receiver). Residual CD is compensated using a finite impulse response (FIR) filter with taps. Polarization effects (PMD and Pol-X-talk) are mitigated using a multiple-input multiple-output (MIMO) structure. The coefficients of the MIMO structure are optimized using the constant-modulus algorithm (CMA) [5–7]. The phase noise is corrected using a multi-symbol phase estimation (MSPE) technique based on the Viterbi-Viterbi algorithm [5–7].

3. RESULTS

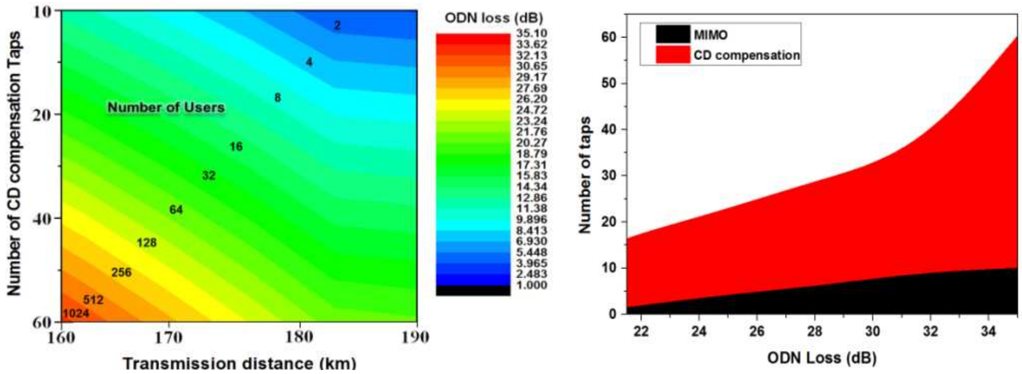
In Fig. 3(a), the maximum achievable transmission distance (19 FIR taps) of 100G-DP-QPSK transmission for upstream and downstream PON directions against the ODN losses is plotted at a targeted average (x- and y-pol) $\text{BER}_{\text{average}}$ of 10^{-3} (assumed FEC limit) for the configuration depicted in Fig. 1, i.e., the rural LR-PON solution. It is shown that the upstream PON performance is very close to the downstream when considering identical launched optical power (LOP) of 0 dBm for both directions. This result reveals that 100-Gb/s could be supported for 1024 split LR-PONs with distances up to 125 km. In Fig. 3(b), results are shown for a fiber loss of 0.2 dB/km at 1550 nm. This can be optimistic for the installed fiber base where cable and splice losses could increase this figure to closer to 0.3 dB/km. In Fig. 3(b), the effects of increasing fiber loss on achievable LR-PON reach is shown keeping all other parameters constant. The fiber loss effects show a reduction in maximum achievable transmission distances for upstream and downstream directions vs. ODN losses of 100G-DP-QPSK at a targeted average BER_{av} of 10^{-3} (note that the LOP for both directions is identical to 0 dBm).

The performance of DP-QPSK coherent systems depends heavily on the level on the DSP em-



(a) (b)

Figure 3: (a) Maximum achievable distances of 100G-DP-QPSK transmission for upstream and downstream vs. ODN losses for BER_{av} of 10^{-3} with inset a received QPSK [x-pol] diagram at 167 km. (b) Comparison of different amount of fiber losses (0.2–0.3 dB/km) for upstream and downstream vs. ODN losses.



(a) (b)

Figure 4: (a) Optimum number of FIR filters for CD compensation vs. maximum achievable distance when considering a $\mathrm{BER}_{\mathrm{av}}$ of 10^{-3} for different amount of ODN losses (colour bars) and number of users. (b) Optimum number of required MIMO and CD compensation FIR taps for a targeted $\mathrm{BER}_{\mathrm{av}}$ of 10^{-3} at fixed 125 km of transmission for different amount of ODN losses. The LOP in all cases is fixed at 0 dBm.

ployed mainly in the complexity (i.e., number of taps) of the FIR filters. By increasing the number of taps used, increased performance can be achieved but at the expense of greater DSP processing and power consumption. In Fig. 4(a), the number of FIR filter taps required for CD compensation is plotted vs. the maximum achievable transmission distance when considering a fixed $\mathrm{BER}_{\mathrm{av}}$ of 10^{-3}, for different amount of ODN losses and number of users (LOP = 0 dBm). It is shown that for higher ODN losses and therefore number of users, the maximum achievable transmission PON distance is reduced (down to $<$ 160 km for 1024 users), whilst the required number of FIR taps increases up to 60. Also shown in Fig. 4(b) is a comparison of the number of taps for MIMO and CD compensation for the 100G-DP-QPSK downstream PON system, corresponding to the LR-PON design of Fig. 2. It is shown that in comparison to the MIMO taps used for mitigating polarisation impairment effects (maximum number is 9 at $\sim$ 35 dB of ODN loss), the requirement for CD taps is much higher as the ODN loss is increased (up to a number of 60 at $\sim$ 35 dB of ODN loss-corresponding to a split of 1024 ways).

4. CONCLUSION

Chain solutions for LR-PON deployment in urban and rural areas have been described and 100-Gb/s point-to-point transmission over the LR-PON infrastructure of these solutions using DP-QPSK modulation has been simulated. The analysis showed that with appropriate FIR filter designs,100-Gb/s transmission can be achieved with at least 512 way split and up to 160 km total distance, which is sufficient for many of the optical paths in a practical situation (e.g., private circuits across large metropolitan area), for point-to-point link from one LR-PON to another LR-PON through the optical switch at the metro nodes and across a core light path through the core network without regeneration.

ACKNOWLEDGMENT

This work was funded by the European Commission's 7th Framework Programme FP/2007-2013 grants 318137 (DISCUS).

REFERENCES

1. Payne, D. B. and R. P. Davey, "The future of fibre access systems," *British Telecom Technology Journal*, Vol. 20, No. 4, 104–114, 2002.
2. http://www.discus-fp7.eu/activities/deliverables, (deliverable D2.1).
3. Yin, X., X. Z. Qiu, G. Torfs, C. Van Praet, R. Vaernewyck, A. Vyncke, J. Verbrugghe, B. Moeneclaey, M. Ruffini, D. B. Payne, and J. Bauwelinck, "Performance evaluation of single carrier 40-Gbit/s downstream for long-reach passive optical networks," *Technical Digest Optical Network Design and Modelling (ONDM) 2014*, Stockholm, 2014.
4. Alcatel-Lucent, 1830 PSS brochure, www.alcatel-lucent.com Ciena 6500 product data sheet, www.ciena.com.

5. Giacoumidis, E., M. A. Jarajreh, S. Sygletos, S. T. Le, A. Tsokanos, A. Hamié, E. Pincemin, Y. Jaouën, F. Farjady, A. D. Ellis, and N. J. Doran, "Dual-polarization multi-band OFDM transmission and transceiver limitations for up to 500 Gb/s in uncompensated long-haul links," *OSA Optics Express*, Vol. 22, No. 9, 10975–10986, 2014.
6. Taylor, M., "Coherent detection method using DSP for demodulation of signal and subsequent equalization of propagation impairments," *IEEE Photonics Technol. Lett.*, Vol. 16, No. 2, 674–676, 2004.
7. Savory, S. J., "Digital filters for coherent optical receivers," *OSA Opt. Express*, Vol. 16, No. 2, 804–817, 2008.