Flexible Optical Metro-access Networks leveraging SOA-based OADM Nodes and DSCM with Power Loading

Zhouyi Hu*, Shiyi Xia, Henrique Freire Santana, Marijn Rombouts, Bin Shi, Nicola Calabretta
Department of Electrical Engineering, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands.
**E-mail: z.hu@tue.nl*

Abstract: We demonstrate a flexible metro-access network exploiting SOA-based OADM nodes and digital subcarrier multiplexing with power loading. Results show that at least 4 nodes can be supported for 40-Gb/s transmission with bandwidth allocation on demand. © 2024 The Author(s)

1. Introduction

To meet the requirements of ruthless growth of many new network services, such as 5G and beyond, cloud computing, and virtual reality, the existing optical metro-access networks are expected to upgrade for higher capacity, flexibility, and lower latency [1]. Moreover, cost and power-sensitive optical system solutions are critical for the network segment that requires deploying high-density optical switching sub-systems such as horseshoe access networks as shown in Fig. 1(a). Although flexible optical metro-access networks can be implemented by employing expensive wavelength selective switches and fast-tunable transceivers [2], it leads to high costs as well as a large footprint. In our previous work, we have demonstrated a lossless and fast reconfigurable optical add-drop multiplexer (OADM) node based on semiconductor optical amplifiers (SOAs) [3], which can be fully monolithically photonic integrated to reduce the cost, footprint, and power consumption [4]. Currently, the traffic handled by the OADM has the granularity of a single wave division multiplexing (WDM) data channel (single-carrier), thus with limited flexibility of the system. Multi-carrier signals, such as digital subcarrier multiplexing (DSCM), have been widely investigated due to their high flexibility in bandwidth allocation. Coherent DSCM can support high bandwidth point to multipoint but at a high cost as it requires a tunable local oscillator and coherent detection [5], [6]. However, in some cost-sensitive scenarios such as the horseshoe metro-access networks, DSCM with intensity-modulated/direct-detection (IM/DD) can deliver flexible bandwidth allocation but at a lower cost. To the best of our knowledge, the performance of an optical metro-access network employing SOA-based OADM nodes and DSCM with IM/DD as a low-cost and flexible solution has not yet been investigated.

In this paper, we experimentally demonstrate a cost-effective metro-access network with flexible bandwidth allocation on demand exploiting the SOA-based OADM nodes and the DSCM with the IM/DD technique. Moreover, to overcome the bandwidth limitation in low-budget IM/DD networks, a simple power loading scheme is investigated and applied, ensuring the same signal quality received by different users. Through a proof-of-concept experiment, we study the performance of the proposed scheme in an example horseshoe network for metro-access applications. The experimental results show that the SOA-based OADM can support at least 4 cascaded nodes with the help of DSCM and power loading. We also show that DSCM IM/DD outperforms the single-carrier pulse-amplitude modulation (PAM-4) direct detection solution (i.e., time-division multiplexing) that can only support two cascaded nodes. We also verify the feasibility of the proposed scheme with WDM DSCM data channels in dynamic drop and add operation for wavelength channel reusing, and results show negligible penalty.

2. Architecture and proof-of-concept experiment

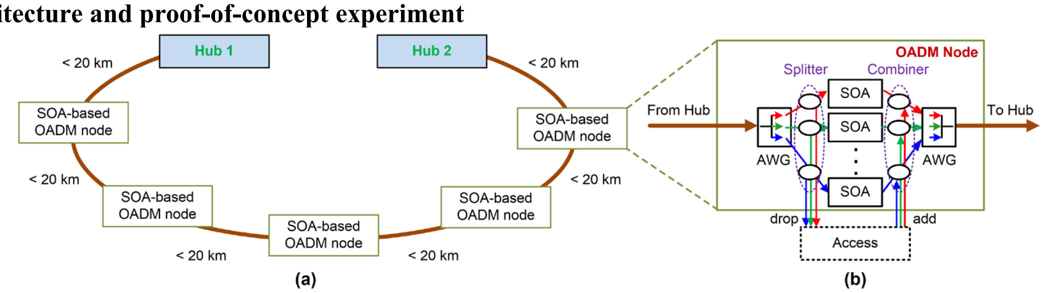

Fig. 1. Architecture of (a) the horseshoe network and (b) the proposed SOA-based OADM node.

Figure 1(a) shows a typical horseshoe metro-access network with SOA-based OADM nodes. Fig. 1(b) shows the SOA-based OADM node capable of dropping/adding and continuing WDM DSCM signals at each node. The OADM consists of a demultiplexer implemented by an arrayed waveguide grating (AWG) followed by a 1×2 3-dB optical power splitters (one port for the drop traffic, and the second one is fed into the SOA gate). The SOAs act as gates and amplifiers to let pass (SOA is turned on) or block (SOA is turned off) each wavelength. Moreover, the SOAs provide amplification to compensate for the OADM and link loss, so no EDFA is required in the horseshoe network. Note that each SOA amplifies a single wavelength, thus no distortions due to cross-gain or cross-phase modulation and four-wave mixing occur. After the SOA gates, a 2×1 optical combiner is then employed to add the traffic to the horseshoe network. The OADM node is therefore able to realize flexible, fast, and lossless control of the WDM traffic thanks to the nanosecond-scale switching and the gain provided by the SOAs.

In this work, we first propose using DSCM and power loading to further improve the flexibility of this architecture compared to the conventional single-carrier formats (e.g., PAM4). We design and implement two proof-of-concept experiments to verify its feasibility; in the first one, only one wavelength (1549.3 nm) is tested but passes through up to 4 SOA-based OADM nodes to investigate the scalability of the proposed architecture. In the second experiment, two wavelengths (1549.3 nm and 1550.9 nm) are transmitted with both dropping and adding traffic to show its performance in a practical 2-node WDM network. The experimental setup is depicted in Fig. 2(a), and the digital signal processing (DSP) used in the transmitter side and the receiver side are shown in Fig. 2(b) and (c), respectively. We can see that the transmitter-side DSP included pseudorandom binary sequence (PRBS, 2^{15}–1) generation, quadrature amplitude modulation (QAM) mapping, upsampling, Nyquist pulse shaping with a root-raised-cosine (RRC) filter, DSCM generation and the power loading based on the pre-estimated channel state information. In this work, 16-QAM symbols are allocated to 4 subcarriers with a bandwidth of 2.5 GHz each, so the aggregate data rate is 40 Gb/s (= 4 bits × 2.5 GHz × 4). The generated digital signal was converted to an optical signal by a 24-GSa/s arbitrary waveform generator and a Mach-Zehnder modulator (MZM). The optical signal was then fed into the horseshoe network. The fiber links employed before each node (No. 1 to No. 4) in the horseshoe network had a length of 6.4 km, 16.8 km, 3.2 km and 1 km, respectively. The dropped traffic at each node was detected by a photodetector (PD) via an EDFA pre-amplifier, optical filter and a variable optical attenuator (VOA) to vary the received optical power (ROP). A 50-GSa/s oscilloscope was finally used to capture the received signal and send it to the receiver-side DSP including down conversion, matched RRC filter, synchronization, resampling, equalization, QAM mapping and bit-error-rate (BER) measurement. The optical spectra of the signal at each node for both single-wavelength and WDM cases are shown in Fig. 2(d) and (e), respectively, indicating an average optical signal-to-noise ratio (OSNR) reduction of ~6 dB from each SOA-OADM node.

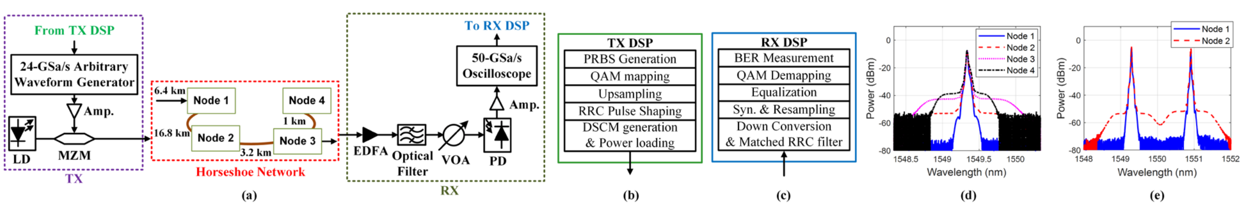

Fig. 2. (a) Proof-of-concept experiment (example traffic dropped at Node 3). DSP at (b) the transmitter side and (c) the receiver side. Spectra (rescaled for easy comparison) of (d) the single-wavelength signal and (e) the WDM signal at the entrance of each node.

3. Experimental results and discussions

We first evaluated the transmission performance at each node to show the scalability of the proposed architecture. Fig. 3(a) shows the average BER performance of the DSCM signal without and with power loading, and the conventional PAM4 signal at the same aggregate data rate dropped at Node 1 and Node 4, respectively. We can see that only the DSCM with power loading can barely meet the hard-decision forward error correction (HD-FEC) requirement (4.7×10^{-3}) at Node 4. We also notice that at Node 4, the signals show better performance at the low ROP region. It is because we optimized the DC bias of the MZM for different nodes due to the cumulative nonlinearity of SOAs. The improvement from power loading can be explained by Fig. 3(b), where the inset is the electrical spectra of the received DSCM signals without and with power loading. We can see that due to the severe bandwidth limitation of our system (~20-dB roll-off at 10 GHz), the 4-th subcarrier had very poor performance, leading to a high average BER of the DSCM signal without power loading. With the help of power loading, the DSCM signal can achieve relatively constant BERs across all subcarriers, thus significantly reducing the average BER and outperforming the conventional PAM4 signal. The estimated SNR of all subcarriers and PAM4 signals dropped at each node are presented in Fig. 3(c), showing an SNR penalty of ~0.5-1.5 dB after each node.

We then emulated an example bandwidth allocation case. For balancing, Subcarriers 1 (best), 2, 3, and 4 (worst) were allocated to Nodes 4 (farthest), 3, 2, and 1 (nearest), respectively. Fig. 3(d) compares the BER (red) and SNR (black) performance of the traffic dropped at each node, showing that only the scheme with both DSCM and power loading can always meet the HD-FEC requirement for all 4 nodes. We also noted that for DSCM without power loading, since Subcarrier 1 (allocated to Node 4) had the highest SNR (see Fig. 3(c)), it maintained the best performance even after passing through more nodes.

We have finally evaluated the performance of the proposed scheme working in a 2-channel WDM network. The BER performance of different schemes at Channel 1 (1549.3 nm) and Channel 2 (1550.9 nm) are presented in Fig. 3(e) and (f), respectively. Results indicate that the 2 channels have similar performance. We have also investigated the performance of the traffic dropped and then added (at the same wavelength) to the network at Node 1 by blocking the wavelength channel (SOA off) and measuring the newly added signal. Results show a negligible penalty of the added signal thanks to the high on/off ratio of the SOA (>40 dB). Meanwhile, when compared to the signal-wavelength case shown in Fig. 3(a), the WDM case shows very similar performance. The power loading can still significantly improve the performance of DSCM, which outperforms the conventional PAM4 format.

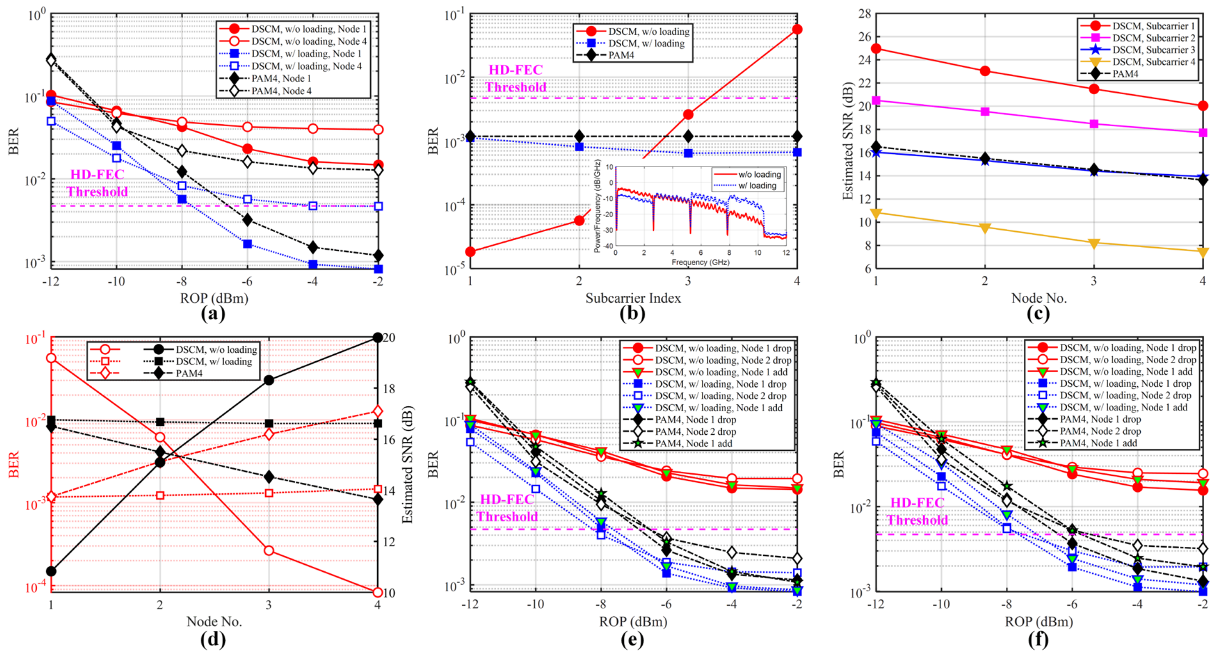

Fig. 3. Single-wavelength network: (a) Average BER vs ROP for different schemes; (b) BER distribution over subcarriers of the DSCM signal (Inset: electrical spectra of the received DSCM signals without and with power loading); (c) BER of different subcarriers/signals dropped at each node; (d) BER (red) and SNR (black) estimated at each node with an example bandwidth allocation (i.e., Subcarriers 1, 2, 3, 4 dropped at Nodes 4, 3, 2,1, respectively). WDM network: Average BER vs ROP for different schemes measured at Channel (e) 1 and (f) 2, respectively.

3. Summary

We have proposed and experimentally demonstrated a flexible and cost-effective SOA-based OADM metro-access network leveraging DSCM IM/DD and power loading techniques. Experimental results verify the operation of a 4-node horseshoe network at an aggregate single-wavelength data rate of 40 Gb/s, flexible bandwidth allocation per node, and better performance than the PAM4 format. It should be noted that the data rate and the number of supported nodes in this work were mainly limited by the low bandwidth of our current equipment, which can be significantly improved by using high-speed ones. WDM and dynamic add/drop operation have been also demonstrated with negligible penalty compared to the single-wavelength case. All results indicate the great potential of the proposed solution for high-performance and low-cost metro-access networks.

Acknowledgements

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