European Conference on Optical Communication (ECOC) 2022 © Optica Publishing Group 2022

Photonically Interconnected Federated Edge-Computing Networks Using Fast Reconfigurable SOA-based OADMs

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Abstract *We propose and demonstrate via BER tests lossless SOA-based optical add/drop multiplexer nodes for low-latency and deterministic photonically interconnected federated edge-computing nodes. Experimental results confirm error-free communication for up to 5 nodes with $<$ 3.5 dB power penalty at 25G NRZ-OOK. ©2022 The Author(s)*

Introduction

The growth of applications with stringent latency requirements requires the redesign of optical networks. To meet latency requirements, data centers (DCs) have been migrating to locations in the edge of the network, therefore reducing the latency to the users by construction. Moreover, new applications such as distributed artificial intelligence models require federated operation of computational resources scattered in the network.

Edge DCs bring an important trade-off between the allocation of computational resources and the optical network infrastructure. The nodes in the metro transport network play a key role in this problem because of their strategic position. They can offer reduced latency to the end users and they can reduce the amount of aggregation required to go to the core.

However, the deployment of electronic switches still increase the latency and the jitter of the network, and require power-hungry opto-electronic conversions. By having more transparent paths, that is, communication paths where the data remain in the optical domain between the ingress point and the egress point in the network, the latency in the network become more deterministic. Optical switches can increase the transparency of the network, providing paths to the signals without leaving the optical domain. By bypassing electronic switches, it is possible to reduce the latency variation in the network associated with buffering in the electronic domain and avoid power-hungry optoelectronic conversions.

Optical switches exist in different technologies and switching times. Switches based on thermo-optic effects are slow[1]. Semiconductor optical amplifiers have features that make them attractive as optical switches. Semiconductor optical amplifiers (SOAs) can be switched between on and off states in nanosecond scale[2], therefore providing a way to gate optical flows very dynamically. Moreover, the gain provided by an SOA can compensate optical losses, therefore making it possible to build lossless optical switches[3]. Besides that, SOAs can be integrated[4], potentially reducing the costs of the devices, which is necessary for the deployment in numerous smaller nodes spread in the network.

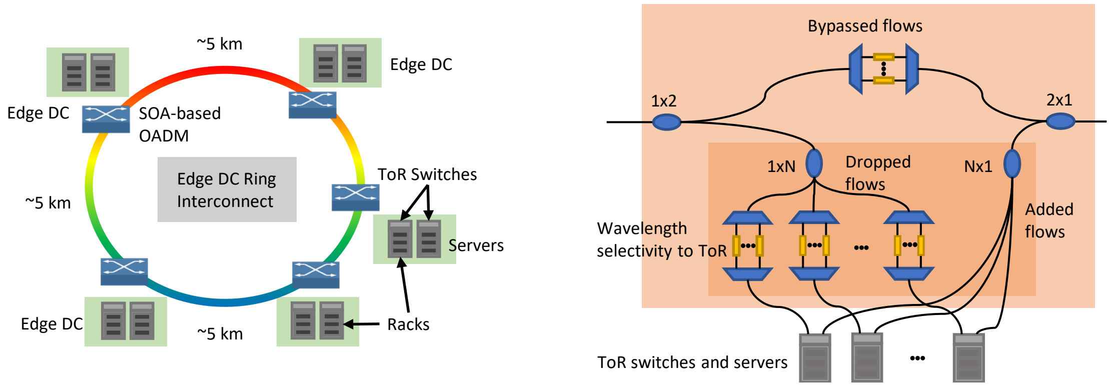
To fully utilize the potential of nanosecond-scale switching of SOAs in providing dynamicity and reutilization of resources, fast controlled networks have been investigated in[5],[6]. In these networks, the control of the optical switches is performed by field-programmable gate arrays (FPGAs) to bring the decisions very close to the hardware. In these networks, network interfaces are connected via a ring using 1×2 optical add-drop multiplexers (OADMs).

The usage of these SOA-based optical switches, however, also poses several challenges. The noise and the non-linearities[7] introduced by every SOA in the link degrades the optical signal-to-noise ratio (OSNR), imposing limits to the transparency of the network.

In this work, we extend the network architecture with SOA-based OADMs to multiple degrees, providing the possibility of connecting multiple interfaces transparently to the ring. Then, we investigate the scalability of this architecture as the optical link crosses multiple nodes transparently in terms of nodes crossed and in terms of datacom resources directly interconnected.

Network Architecture

We consider a ring interconnect with edge data centers, as shown in Fig. 1a). This interconnect contains nodes with network interfaces that ag-



(a) (b)

Fig. 1: (a) Network overview showing the edge DC ring interconnect and (b) node architecture showing the add and drop sections with wavelength blocker elements.

gregate the data flows coming from the access. The nodes also contain edge DCs which handle the latency-sensitive flows. The edge DCs have racks containing servers. The racks have a top-of-rack (ToR) switch, equipped with the transmitters and receivers to the ring. The data flows can travel transparently through the ring from one node to another, according to the configuration of the SOA-based OADMs.

The node architecture is shown in Fig. 1(b). At the entrance of each node, a splitter divides the traffic to be dropped and the traffic that will cross the node. The combination of 2 arrayed waveguide gratings (AWGs) in a demux-mux configuration and SOAs between them is a wavelength blocker (WBL) element. The first AWG of the WBL separates the wavelengths to multiple SOAs acting as gating elements. Each SOA therefore receives only one wavelength, which means that the architecture can operate on a per wavelength basis. The SOAs then are turned on and off by an FPGA-based fast optical switch controller, allowing the reutilization of wavelengths in the ring, once one channel is dropped to a node.

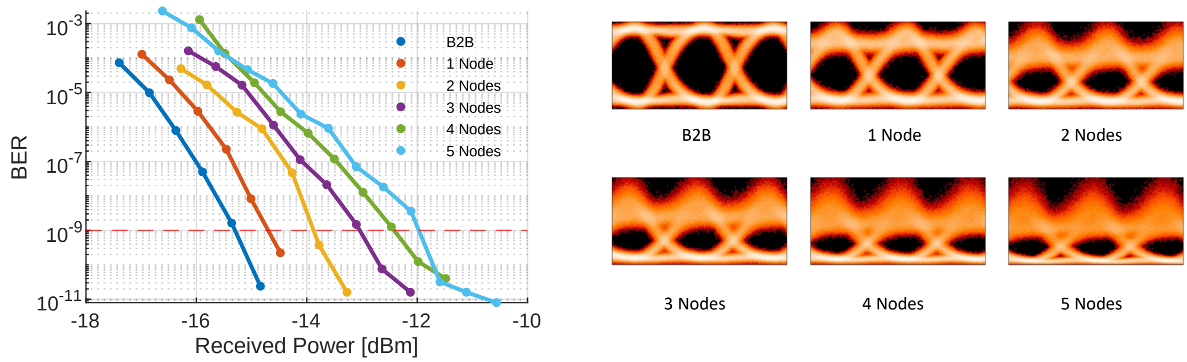
After the 1×2 splitter in the entrance of the node, a further 1×N splitting occurs, followed by wavelength blocker elements which deliver the wavelengths to the receivers. This forms the drop section of the architecture. The 1×N splitter can be chosen to serve a higher number of interfaces. The add section of the interface is comprised of N×1 combiner, which is further combined with a 1×2 combiner. This 1×2 combiner joins the optical flows that skipped the node with the flows originated at the node. We assume that the node controller is able to prevent potential contentions in the adding optical flows to the ring.

When the transmission occurs between adjacent nodes, the total losses are given by the losses of the combiners in the add section of the origin node, the splitters of the drop section of the destination node and the fiber span. In a configuration with N = 2, this amounts to a 12-dB loss plus the span loss, and there is one SOA in the path to (partially) compensate these losses. In a configuration with N = 4, the splitting losses amount to 18 dB. When the transmission spans more nodes, for every crossed node there are additional 6 dB of loss (regardless of N) and the losses of the fiber span, but there is also an SOA to provide gain.

Experimental Evaluation

We investigate different scenarios, with transmissions up to 5 nodes, that is, crossing 5 SOAs. In all the evaluated scenarios, the fiber links between the nodes are emulated by optical attenuators of 1 dB, corresponding to 5 km of fiber. We assume that the dispersion can be digitally compensated at the scenarios investigated.

The experiments were performed with a continuous laser source emitting at $\lambda = 1557.36$ nm. After the laser source, a polarization controller (PC) was used to optimize the state of polarization. Then, the light was fed to a Mach-Zehnder modulator, which was driven at 25 Gbps NRZ-OOK with a pseudorandom binary sequence (PRBS) with length of 2^{31}-1 bits. An erbium-doped fiber amplifier (EDFA) was used to compensate for the modulator losses and the signal was fed to the system. In the output of the system, a variable optical attenuator was used to perform the power sweep. Then the signal was split with a 90/10 coupler. The 10%-port was fed to an optical spectrum analyzer (OSA) for the spectral analysis. The 90%-port was fed to a photodetector with integrated transimpedance amplifier (TIA) to convert the signal to the electrical domain. The output of the PD



(a) (b)

Fig. 2: (a) bit error rate (BER) performance for up to 5 node crossings and (b) respective eye diagrams.

was connected to the error analyzer module.

We evaluated the scenarios for 1×2 and 1×4 splitters, meaning that the node can support 2 and 4 ToR switches respectively (that means 80 and 160 servers respectively). The difference in the architecture is the additional 3-dB loss of the add section in the origin node and the drop section of the destination node.

Results

Fig. 2a shows the BER performance for the architecture with 2 ToRs up to 5 node crossings. We see that that every transparently crossed node introduces a penalty, whose value is slightly different. We see a penalty of of 0.8 dB from 1 to 2 nodes, and from 2 to 3 nodes. From 3 to 4 nodes, the penalty is 0.6 dB, and from 4 to 5 nodes, the penalty is 0.5 dB. The total penalty of 5 nodes with respect to the back-to-back measurement is $<$ 3.5 dB Fig. 2b shows the corresponding eye diagrams. We see that the eye diagram gets increasingly distorted in the top rail as more nodes are crossed.

Fig. 3 shows the BER performance for the architectures with 2 ToRs and 4 ToRs in 2, 3 and 4 node crossings. The bias current of the SOAs were kept the same, only the additional 3-dB loss was added to the add part of the origin node and the drop part of the destination node. We see that no significant difference is observed in the scenarios with 2 and 3 crossings. As for the scenario with 4 crossings, the case with 4 ToRs performed better than the case with 2 ToRs. This is due to the fact that the additional losses changed the input power of the SOAs, putting them in an operation region that yielded less distortion.

In all evaluated scenarios, the transparent links were error-free at $1{\times}10^{-9}$ BER, showing the viability of taking the transparency to the ToR switches in the edge data centers.

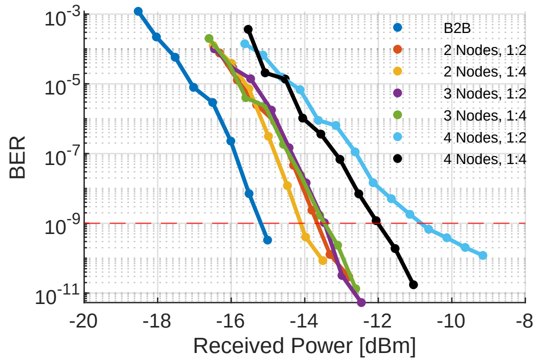


Fig. 3: A comparison of BER performance for 2, 3 and 4 node crossings for the scenarios with 2 ToRs and 4 ToRs.

Conclusions

We proposed an edge node architecture which can transparently connect multiple ToR switches in a ring interconnect of edge DCs. We demonstrated error-free communication in all evaluated scenarios, showing the viability of this architecture.

Acknowledgements

This work was funded by the TU/e-KPN Smart Two project.

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