50Gb/s Optical Wireless Data Center Network Architecture Using SOA-based Wavelength Selector and AWGR

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Abstract *We experimentally demonstrate a fast optical wireless datacenter network architecture using nanoseconds SOA-based wavelength selector and Arrayed Waveguide-Grating Router for optical switching. 4x4 prototype experiments show error-free 50Gb/s OOK per link with power penalty <2dB.*

Introduction

The wide scale application of new emerging technologies such as big data, cloud computing and internet of things impose heavy pressure on Data Center Networks (DCNs). In order to meet the demand of these applications in terms of high capacity, fast reconfiguration, good scalability and low cabling complexity, DCNs needs fast deployment and convenient upgrade. Conventional wired DCNs, which have drawn much research attention[1], need huge amount of cables for upgradation, leading to issues such as wire ducting and space utilization. Besides, the wired hierarchical tree-based DCNs architecture fails to adapt to the unpredictable traffic patterns by using a fixed topology[2]. A promising alternative solution to the above mentioned shortcoing is to introduce optical wireless communication (OWC) technology into DCNs. It removes the cable complexity and provides a significantly flexible architecture for good scalability, fast reconfiguration and relocation. The wide frequency range offer a potentially high capacity[3]. Moreover, the negligible waveguide dispersion and almost zero attenuation make OWC being considered as a next frontier for ultra-high data rates with low transmission power.

Several optical wireless technologies have been employed for establishing the intra and inter-connection links of DCN, such as MEMS[4], digital micromirror device[5], switchable mirrors[6] and pedestal mounted transceiver module with height and rotation control[7]. Those approaches employ milliseconds reconfiguration time of the switch that can result in low throughput, while others works provide only numerical investigations of the DCN architectures.

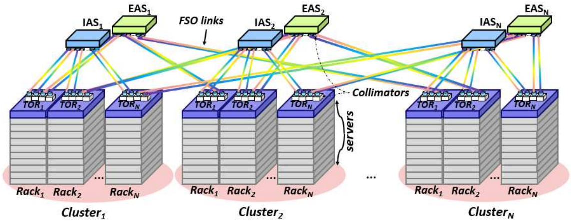

Fig. 1: A schematic of OWC-DCN architecture based on AWGR; FSO: free space optical; IAS: intra-cluster AWGR based switch; EAS: inter-cluster AWGR based switch; ToR: Top of rack.

In this work, we propose and experimentally demonstrate a practical optical wireless DCN (OW-DCN) architecture based on nanoseconds semicinductor optical amplifier (SOA)-based wavelength selectors (SWS) at the top-of-the-rack (ToR) switches and arrayed waveguide grating router (AWGR) for the intra- and inter-cluster interconnection. The data transmission between the ToR switches is done by properly tuning the central wavelength of the transceiver controlled by the SWS. At the AWGR, based on the central wavelength of the data channel, the data is forwarded to one of the AWGR output ports, thus switching the data channel to reach any of the target ToRs. The FPGA-based switch scheduler of the proposed OW-DCN concept has been experimentally verified as well as the transmission performance evaluated with one cluster 4×4 racks DCN prototype implemented by the SWS and a 4×4 AWGR. Results show that error free transmission at 50Gb/s NRZ-OOK with limited power penalty.

SWS based optical wireless DCN architecture

The proposed fast optical wireless DCN architecture based on SWS and N×N ports AWGR are shown in Fig. 1. The network consists of N culsters connected by inter-cluster AWGR based switches (EAS), while each culster groups with N ToRs by using intra-cluster AWGR based switch (IAS). For each ToR switch, K servers are interconnected. The packet forwarding is based on the fixed cyclical-permutation-based routing matrix between the input and output ports of AWGR. The functional blocks of ToR switch is shown in Fig. 2(a). It is equipped with two pairs of collimators for two bi-directional free space transmissions. One pair of collimators steers and receives the light signal from IAS for intra-cluster communicaion, while another pair of collimators is used for inter-cluster communication with EAS. The incoming traffic of ToR switch can be classified into intra-rack traffic, intra-cluster traffic and inter-cluster traffic. For these packet traffic,

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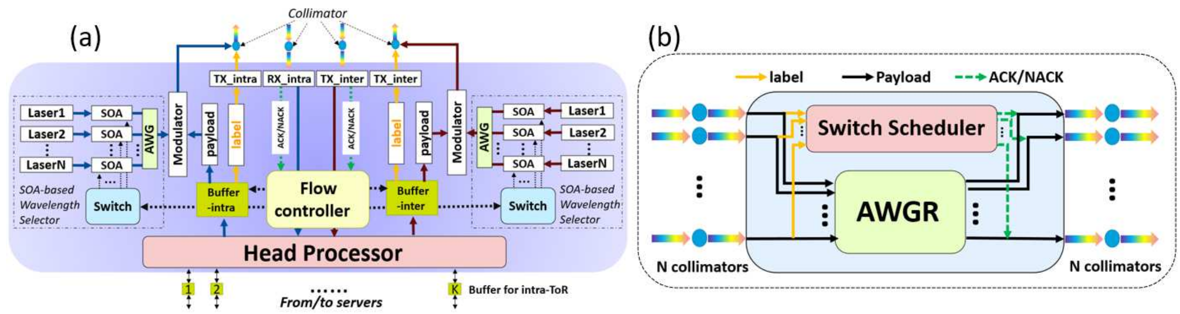

Fig. 2: (a) The functional blocks of ToR switch; (b) The functional blocks of IAS (intra-cluster AWGR) and EAS (inter-cluster AWGR); TX: transmitter; RX: receiver.

the head processor will firstly check the packet header for their destination. If the packet is destinated in same rack, the packet is directly exchanged between servers. For packet destines to a server in different racks at same or different cluster, the packet is forward to intra-buffer or inter-buffer waiting for transmission, respectively. The packet is transmitted only if get a positive ACK from the switch scheduler. For each packet, an optical label carrying the packet destination and priority (when contention happened, packets with higher priority will be passed, while packets with lower priority will be blocked) information is forwarded in advance to the FPGA-based scheduler. According to the feedback from the scheduler, the central wavelength of the optical payload is selected to match the wavelength routing map of the AWGR. As shown in Fig. 2(a), the wavelength selection is realized by the SOA-based fast SWS consisting of an array of lasers at different wavelength (matched with the AWGR wavelengths), an array of SOA gates for selecting the laser (or lasers in case of multicasting), and an AWG as multiplexer. After the SWS, an optical modulator is used to convert the electrical packet to optical packet. Note that the SWS and the optical modulator can be photonic integrated decreasing the cost and footprint. The optical payload is then sent through the optical wireless link via collimators to the AWGR based IAS (or EAS). The schematic of the IAS (or EAS) wavelength routing switch is schematically shown in Fig. 2(b). It has N×N input and output ports. For each pair of the input and output port, two collimators are equipped for the bi-directional free space transmissions with each ToR. The optical label carrying the packet destination and priority from ToR is delivered to the FPGA-based scheduler, which processes all the optical labels of the data coming from different intra (or inter) cluster ToRs. The scheduler checks possible contentions (packets with same ToR destination at the same time slot), and sends positive ACK signal (request granted and data packet can be successfully forwarded to the destination ToR) or negative ACK (NACK, request refused due to packet contention) back to each ToR for implementing the switch schedule. Only if the ToR receives an ACK signal, the payload is forwarded.

It is worth to note that at most two-hops communication is needed for interconnecting racks within this OW-DCN. And it allows different path connection between racks, which showing the viability of supporting different load balancing algorithm and improving the resilience of the DCN. Moreover, the proposed architecture is readily scalable to larger DCNs by using an AWGR with more ports. The number of interconnected ToRs scales as N×N with a N×N ports AWGR. Prototypes with 90×90 ports and 50GHz AWGR have been demonstrated[8]. By using this AWGR, a DCN up to 324,000 severs (if each ToR groups 40 servers) could be connected. Besides, the negligible dispersion, almost zero attenuation due to the transparency of the optical wireless links allows scaling up to higher data rates per link. Aside from this, the capacity of each link can also be dynamically added by using the cyclically speciality of AWGR without changing the infrastructure.

Experimental set-up and Results

The proposed OW-DCN has been experimentally verified and demonstrated with one cluster prototype implementing a 4×4 racks DCN. The ToRs and switch scheduler have been implemented using four FPGAs Xilinx Ultrascale, equipped with 10Gbps SFP transceivers for the communication between the ToRs and the switch

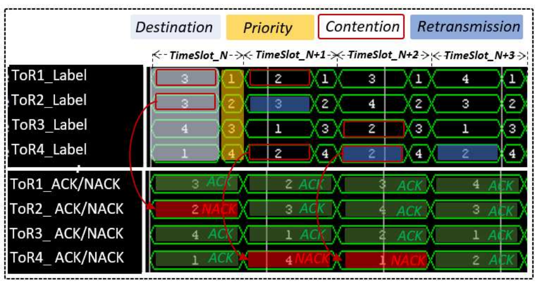

Fig. 3: Label signals and ACK/NACK at the FPGA-based switch scheduler.

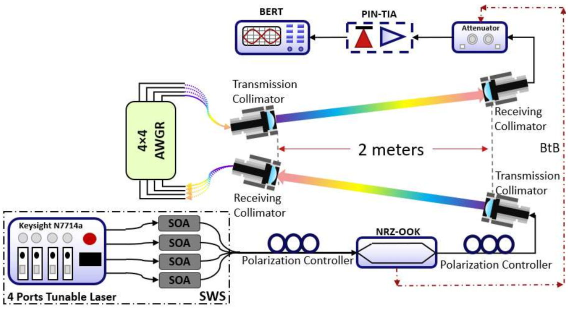

Fig. 4: Experimental set-up of one cluster with 4×4 racks OW-DCN.

scheduler to implement the requests (optical labels carrying destinations and priorities) and the scheduler responses (ACK/ NACK). The priority is set as '1>2>3>4', which means ToR1 has the highest priority). As we can see from Fig.3, the scheduler processes all the optical labels with destination and priority information, checks the possible contentions and sends the ACK and NACK back to the corresponding ToRs. As shown in Fig. 3, requests from ToR2 in time-slot N and from ToR4 in time-slot N+1 are refused due to the contention with requests from ToR1, while request from ToR4 in time-slot N+2 are refused due to the contention with requests from ToR3. Then NACKs are generated by the scheduler. The ToRs, which received NACK (ToR2 in time-slot N+1, ToR4 in time-slot N+1 and N+2), will retransmit the packet by sending the label again at next time slot. If there is no contention, the scheduler sends ACK to all the ToRs, as shown in time-slot N+3.

Once verified the operation of the switch scheduler, we have assessed the 50Gb/s data plane transmission performance of the proposed OW-DCN. The experimental setup is shown in Fig. 4. One 4×4 AWGR with 200 GHz channel spacing and an SWS have been used as a proof of concept demonstration of one cluster with 4×4 racks DCN. The optical wireless path between collimators for AWGR and collimators for ToRs is around 2 meters. All the input and output port of the 4x4 AWGR based DCN have been assessed. Four SOAs and a four tunable lasers are used as a prototype of the SWS. As the AWGR is polarization dependent, a polarization controller was used to adjust the polarization at the transmitter side. Tab. 1 shows the wavelength routing map of the AWGR. According to this, the

Tab. 1: Wavelength routing map of AWGR

Wavelength (nm)	Port 1	Port 2	Port 3	Port 4
Port 1	1559.08	1560.70	1562.30	1557.46
Port 2	1560.64	1562.26	1557.40	1559.02
Port 3	1562.26	1557.38	1559.00	1560.62
Port 4	1557.36	1558.96	1560.58	1562.18

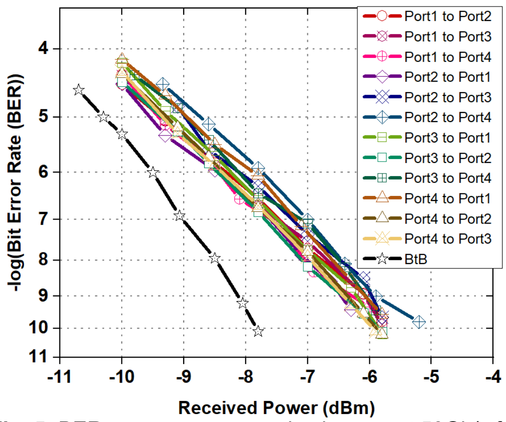

Fig. 5: BER curves versus received power at 50Gb/s for the links between ToRs.

wavelength routing from each port of the tunable laser has been set in advance. To tune the central wavelength of the transmitter, the SOA gates of the SWS have been turns on/off properly. A 50Gb/s Mach-Zehnder modulator (MZM) was used to generate NRZ-OOK data with PRBS-31. The 50Gb/s optical data was coupled into a triplet lens collimator (Thorlabs TC18FC-1550), and then launching into free space to the AWGR. The transmitted optical signal from the collimator is around 8dBm, which is below the eye safety limit at λ>1.4um. Lower power is possible by optimizing the losses of the AWGR, which is 8.5dB. After passing through the AWGR and the free space link, the 50Gb/s optical data is captured by the collimator and detected by the ToR receiver. A BER tester is used for measuring the bit error rate at the receiver. The Back-to-Back (BtB) measurement is performed as using a single mode fiber connects directly from the output of modulator to receiver. All the 12 links of this 4x4 AWGR based 4×4 racks DCN have been assessed as shown in Fig.5. Experimental results confirm that 50Gb/s error-free (BER<1×10^{-9}) transmission has been measured with a penalty of about 2dB with respect to the reference BtB transmission.

Conclusion

A novel scalable and fast optical wireless DCN architecture based on nanoseconds SOA-based wavelength selectors, scheduler, and N×N port AWGR has been presented and verified. The SOA-based wavelength selector and modulator can be photonic integrated for low cost and footprint. The FPGA-based switch scheduler has been experimentally validated by successfully processing the ToRs requests and generation of ACK/NACK responses. Moreover, experimental assessment of a 4×4 racks OW-DCN confirms error-free transmission with power penalty less than 2dB at BER of 1E-9 for 50Gb/s OOK data.

References

[1] X. Xue *et al.*, “ROTOS: A Reconfigurable and Cost-Effective Architecture for High-Performance Optical Data Center Networks”, *J. Light. Technol.*, vol. 38, no. 13, pp. 3485–3494, 2020.

[2] A. S. Hamza, J. S. Deogun, and D. R. Alexander, “Wireless communication in data centers: A survey”, *IEEE Commun. Surv. Tutorials*, vol. 18, no. 3, pp. 1572–1595, 2016.

[3] T. Koonen, K. Mekonnen, Z. Cao, F. Huijskens, N. Q. Pham, and E. Tangdiongga, “Ultra-high-capacity wireless communication by means of steered narrow optical beams”, *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.*, vol. 378, no. 2169, 2020.

[4] P. Deng, T. Kane, and O. Alharbi, “Reconfigurable free space optical data center network using gimbal-less MEMS retroreflective acquisition and tracking”, *International Society for Optics and Photonics*, Vol. 10524, p. 1052403, 2018.

[5] M. Ghobadi *et al.*, “ProjecToR: Agile reconfigurable data center interconnect”, in *Proc. the 2016 ACM SIGCOMM Conference*, 2016.

[6] N. Hamedazimi *et al.*, “FireFly: A reconfigurable wireless data center fabric using free-space optics”, *Comput. Commun. Rev.*, vol. 44, no. 4, pp. 319–330, 2015.

[7] N. A. Riza, “The camceiver: Empowering robust agile indoor optical wireless for massive data centres”, In *Proc. 42nd Int. Conf. Telecommun. Signal Process. TSP*, 2019, pp. 445–448.

[8] S. Yoo, J. K. Lee, and K. Kim, “Suppression of thermal wavelength drift in widely tunable DS-DBR laser for fast channel-to-channel switching”, *Opt. Express*, vol. 25, no. 24, p. 30406, 2017.