Experimental Assessment of a Novel Optical Wireless Data Center Network Architecture

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Abstract *We propose a novel optical wireless data center network based on passive diffractive optics and fast tunable transmitters. Transmission performance of the proposed network with 8×8 racks is assessed with 20-Gb/s NRZ-OOK. Results show a maximum power penalty of 1dB.*

Introduction

With the emerging of cloud computing paradigm, Internet of things, data-rich applications, and 5G, the data centers (DCs) are experiencing massive traffic explosion[1-2]. High throughput, low latency, fast reconfigurable, high scalability, low cabling complexity interconnections are desired properties for communication inside the data center, which requires technological and architectural innovations. The majority of published works have focused on wired DCN[3-4] with copper and optical fiber cables used for intra- and inter-cluster communication[5-6]. Despite its merits, the inevitable cables bring complexity in terms of space utilization, heat removal and reconfigurability, and limit the flexibility, connectivity and scalability of the deployed topology. A promising efficient alternative solution to the above mentioned issues is to introduce optical wireless communication (OWC) technology into DCN. OWC technology offers another wide unregulated wireless spectrum range[7]. Moreover, it achieves around 1.5 times faster speed than the optical fiber communication. Besides, a much higher data rate can be achieved thanks to the negligible (waveguide) dispersion and attenuation. Furthermore, no-cable setup allows for fast reconfiguration and relocation, and it has the potential of providing on-demand links which adapt to the changing and bursty traffic patterns within DCNs.

In this work, we propose and experimentally assess this novel optical wireless DCN architecture utilizing a passive diffractive grating and a fast tunable transmitter. The connection between the top-of-the-rack (ToR) switches is done by changing the wavelength of the tunable laser, which in turn changes the exit angle of light out of the grating, hence extremely fast switching is feasible (sub-nanosecond wavelength switching independent of the tuning range was demonstrated in [8]). Numerical simulation shows our OWC concept can be scaled up to 32×32 ToRs (having 40960 servers in total) while achieving a 0.53nm crosstalk free bandwidth in the C-band window. The transmission system and performance of one cluster within an 8×8 DCN by an off-the-shelf grating and a C-band tunable transmitter has also been experimentally demonstrated at 20-Gb/s NRZ-OOK, resulting in a maximum power penalty of 1dB.

Optical wireless DCNs architecture

The optical wireless DCN architecture we proposed is outlined in Fig. 1(a). The network is divided into N clusters, and each cluster consists of N racks. For one rack, K servers are

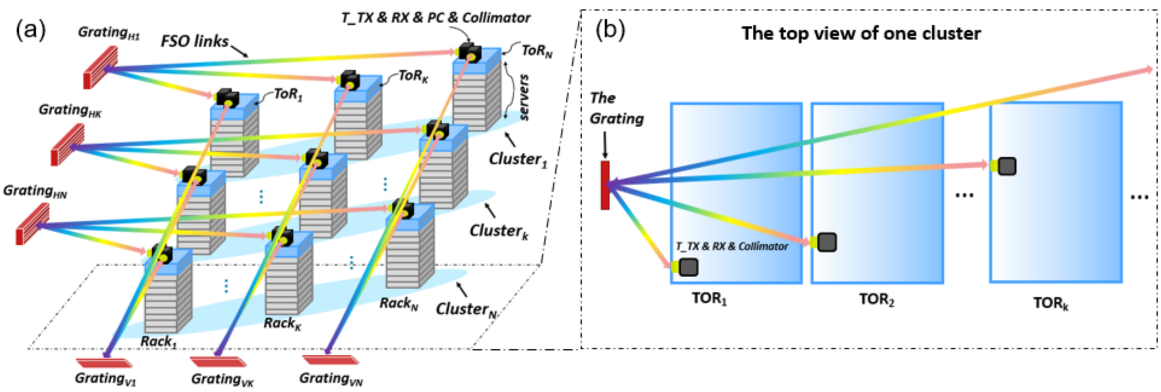

Fig. 1: (a) A schematic of OWC-DCN architecture based on passive diffractive optics and fast tunable transmitters; (b) Top view of one cluster of the OWC-DCN; FSO: free space optical; RX: receiver; T_TX: tunable transmitter.

interconnected by a ToR switch. Each ToR employs two parallel optical links equipped with transmitter, receiver and collimator connected to the horizontal grating ($Grating_{Hx}$) and vertical grating ($Grating_{Vx}$) for the intra-cluster and inter-cluster communication. The $Grating_{Hx}$ interconnects N ToRs within one cluster, while the $Grating_{Vx}$ interconnects N ToRs from different clusters. The top view of one cluster is shown in Fig. 1(b). The communication between ToRs within one cluster is implemented by the cooperation of fast tunable laser T_Tx and optical gratings Hx. For this interconnection, collimators with fast T_TX are placed on top of each rack and positioned in different angles from the grating for the transmission and receiving. When tuning the wavelength of the T_TXs, the collimated incoming light signal from one ToR is steered to the grating and then directed to the destined ToR. The direction angle of the reflected signal depends on the wavelength of the incoming signal. The $Grating_{Vx}$ is employed for the inter-cluster communication between ToRs of different clusters in a similar manner.

Scalability investigation

The scalability of this OWC-DCN depends on the tuning range of T_TXs (96 nm wide tuning range was demonstrated in [9]) and the design of the gratings. Calculations are conducted to fully investigate the scalability using collimator with aperture of 15mm (based on Thorlabs TC18FC-1550) and a real scale of DCN. C-band/L-band/S-band T_TX has been employed to DCNs consisting of 256 (16×16) ToRs and 1024 (32×32) ToRs. The spectral band is defined as the wavelength spectral range which reaches the aperture of the collimator. Since this light signal can be collimated into a SMF by a well-deigned collimator, this spectral band can be used for estimating the potential bandwidth for each free space link after the crosstalk and noise evaluation. The specific interconnection of one ToR is shown in the Fig. 2. The results are presented in the Tab.1. It shows that for the L band (60nm) and S band (70nm) T_TX, a spectral band is around 2nm for a DCN with16 × 16 ToRs, while it is around 1nm for a DCN with 32 × 32 ToRs. Thus, this OWC-DCN may have the potential to realize data rate beyond 100Gb/s, as described in [10]. When the tuning range decreases to 35nm (C-band), the spectral band decreases almost half to be 1.15nm and 0.53nm for a DCN with 16×16 ToRs and 32×32 ToRs, respectively. This is due to the decreasing of the tuning range. Moreover, better results could be reached by deploying gratings working in lower order of these spectral band.

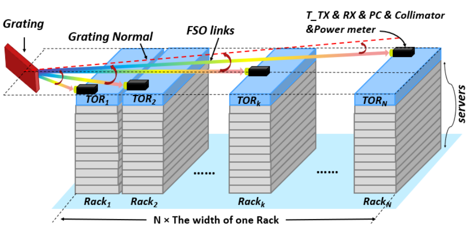

Fig. 2: Interconnections of one cluster within the proposed OW-DCN architecture.

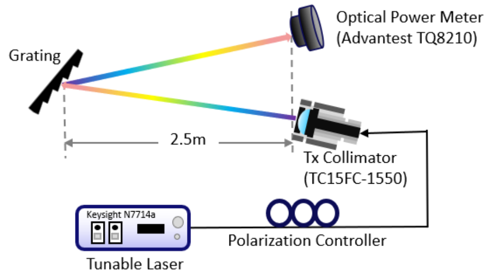

Fig. 3: Experimental setup for power loss and crosstalk measurement.

Tab. 1: System parameters in simulation

ToR counts/ cluster	λ-band	Grating Parameters: Blazed angle [deg]; Grooves/mm	Spectral Width [nm]
16	C	62.52; 26.66	1.15
	L	49.15; 36.47	2.01
	S	42.89; 45.52	2.35
32	C	68.19; 35.85	0.53
	L	56.35; 40.13	0.94
	S	50.33; 51.47	1.11

Experimental verification

Due to the limited equipment , we build a compact experimental setup for the performance measurement of one 8×8 DCN with C-band T_TX to characterize the power loss and crosstalk of the proposed OWC-DCN architecture, as shown in Fig. 3. An echelle grating of 31.6 grooves/mm with a blazed angle of 63 degree (Thorlabs GE2550-0363) is placed over 2.5 meters away from the collimator (Thorlabs TC18FC-1550) and the optical power meter. As the grating is polarization dependent at different wavelength, a polarization controller has been used to adjust the polarization at the transmitter. Tab. 2 gives the connectivity wavelength mapping for this 8×8 DCN. We evaluate the power loss across these wavelengths. The optical power loss is characterized as the power difference measured just before the Tx lens collimator and received by the optical power meter. Crosstalk is defined as the average received power of one optical link

Tab. 2: Connectivity map in wavelength

Wavelength (nm)	ToR1	ToR2	ToR3	ToR4	ToR5	ToR6	ToR7	ToR8
ToR1		1562.89	1560.43	1557.92	1555.38	1552.80	1550.18	1547.53
ToR2	1562.89		1558.00	1555.49	1552.95	1550.37	1547.75	1545.10
ToR3	1560.43	1558.00		1553.03	1550.48	1547.90	1545.29	1542.63
ToR4	1557.92	1555.49	1553.03		1547.98	1545.40	1542.78	1540.12
ToR5	1555.38	1552.95	1550.48	1547.98		1542.86	1540.24	1537.58
ToR6	1552.80	1550.37	1547.90	1545.40	1542.86		1537.66	1535.00
ToR7	1550.18	1547.75	1545.29	1542.78	1540.24	1537.66		1532.38
ToR8	1547.53	1545.10	1542.63	1540.12	1537.58	1535.00	1532.38	

from the adjacent links. Fig. 4 and Fig. 5 report the optical power loss and the crosstalk respectively. The grating contributes at max 6.84dB of optical power loss collectively. The main power loss contributions are the loss of the grating and misalignment. The crosstalk in the free space path is measured to be as low as -36dB.

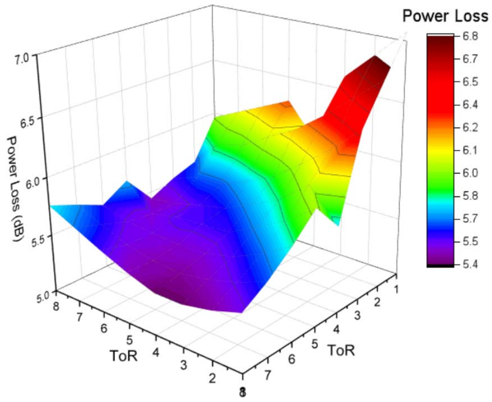

Fig. 4: Power loss performance

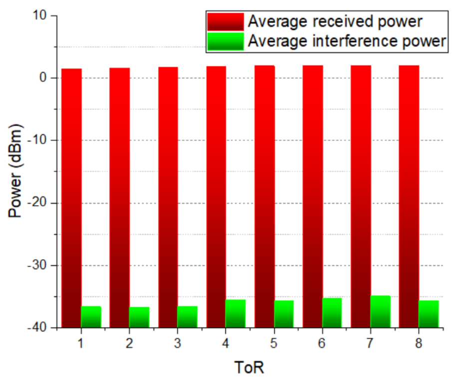

Fig. 5: Received optical power. Difference between red and green bars indicates the crosstalk level.

Fig. 6 shows an experimental setup configured with around 2 meters free space distance to investigate the transmission performance. It consists of three ToRs (ToR1, ToR5 and ToR8) and three collimators from Thorlabs (TC18FC-1550 for ToR1 and ToR5, F810FC-1550 For ToR8) and the same echelle grating as the one in

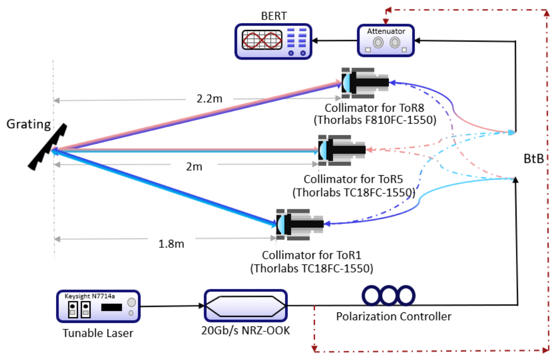

Fig. 6: Experimental setup for one cluster within an 8 × 8 OW-DCN.

power loss and crosstalk measurement. The light signal was modulated using an amplitude modulator driven by 20Gb/s pattern generator with PRBS31. Firstly, a Back-to-Back (BtB) measurement is carried out by connecting the output of the modulator directly to the receiver. After that, the modulated optical signal is fed into the collimator via the polarization controller, and thus launched into the free space DCN. The average transmitted optical power measured before the collimator is around 0 dBm, which is below the eye safety limit at λ>1.4um. The output signal is analysed with a bit-error rate tester (BERT). The link performance, represented by the BER values versus the receiver sensitivity, is plotted in Fig. 7. All the transmission links show error-free operation at data rate of 20Gb/s with a negligible power penalty of less than 1dB at BER=10^{-9} with respect to the BtB measurement . The slightly different power penalty between the six links is mainly due to the different collimator. For the collimator used for ToR8, it has a smaller full-angle divergence (0.016°) compared to the collimator for ToR1 and ToR5 (0.034°), which results in less captured power.

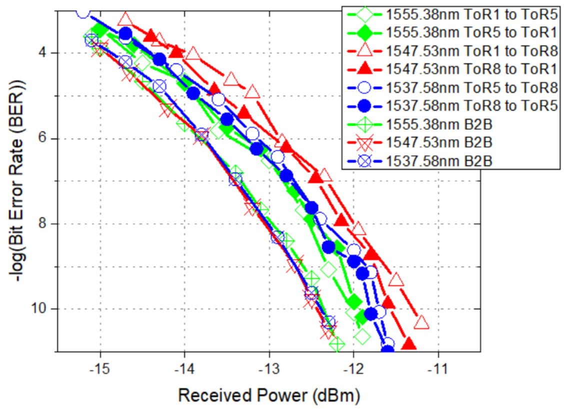

Fig. 7: Link performance versus received power at 20Gbps.

Conclusion

We have introduced and experimentally demonstrated a novel OWC-DCN architecture based on a diffractive grating and a fast tunable transmitter. Scalability studies indicate that the OWC-DCN architecture allows for 1.11nm spectral width for each free space transmission links for a DCN with 32× 32ToRs, which means the optical links within this OWC-DCN may have the potential to realize data rate beyond 100Gb/s. Further improvement is expected by deploying a wider spectrum band and a low order grating. Moreover, a proof-of-concept system based on an 8×8 DCN has been experimentally demonstrated which shows free space switching transmission system with < -36dB cross-talk and 20Gb/s error free operation with a maximum power penalty of 1dB.

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