Real-time Full-Duplex 112Gbps PAM-4 Optical Wireless Transmission for Optical Wireless Data Center Networks

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Abstract *We have proposed a full-duplex, high-capacity optical wireless communication system for an optical wireless data center network. Real-time full-duplex transmission with 112Gb/s pulse amplitude modulation-4 signals have been experimentally demonstrated below the forward error correction threshold with a power penalty of less than 1.5dB.*

Introduction

The proliferation of cloud computing, 5G services, and big data applications have accelerated the expansion of data traffic within data center networks (DCNs) over the past decade [1]. To keep up with demand, next-generation DCNs require massive network capacity and ultra-high bandwidth. Moreover, a flexible, scalable, and cost-effective DCN architecture is highly desirable. Optical wireless data center networks (OW-DCNs) that enable optical wireless (OW) communication technology and pure optical switching technology offer a promising solution. By incorporating OW technology into DCNs, a number of advantages can be achieved, including the ability to overcome the inherent interconnection limitations of traditional wired DCNs by using plug-and-play wireless modules, providing significantly wider license-free bandwidths for higher data rates [2]. In addition, benefiting from optical transparency, the optical switching operation eliminates formant-dependent ports, which enhances scalability for higher data rates while being cost and energy efficient [3][4].

Although there has been progress in OW-DCN research, the majority of studies employ mechanically or electrically operated devices for OW connections and switching, which result in slow switching speeds, high latency, poor reconfigurability, and a complex control system [5]–[7]. In addition, experimental demonstrations have been limited and mainly involved unidirectional transmissions [8]–[10], with high data rates achieved only through a direct line-of-sight transmission via lens systems without any optical switching operations [9]. However, the practical implementation of an OW-DCN urgently required the development of a high-capacity, full-duplex OW transmission network with fast optical switching capabilities.

In this paper, we propose a novel OW-DCN structure based on a high-capacity, full-duplex OW communication system, and a fast optical switching unit employing arrayed waveguide grating routers (AWGRs) and semiconductor optical amplifier (SOA)-based wavelength selectors. In [11], we have experimentally demonstrated the fast and all-optical packet switching by using a unidirectional OW communication system with a link capacity of 50Gb/s. Thereby, we take a step towards implementing a full-duplex, high-capacity OW communication system for the proposed OW-DCN. Experimental results indicate that the proposed system is capable of achieving full-duplex transmission with 56Gbaud pulse amplitude modulation (PAM)-4 signals with less than a 1.5dB power penalty compared to back-to-back transmissions under a forward error correction (FEC) limit of BER=3.84×10^{-3}.

Principle of the OW communication system-based OW-DCN

The proposed OW communication system based OW-DCN is depicted in Fig. 1(a). The network consists of *N* clusters, each with *N* racks. For each rack, *K* servers are connected via the Top of Racks (ToRs). The fast optical switching between the racks is accomplished through the use of passive $N\times N$ port AWGRs and fast-tunable transmitters (TXs). The AWGR is implemented on the optical switch side as shown in Fig. 1(b), while fast tunable TXs are implemented on the ToR side using a SOA-based wavelength selector (SWS) and Field-Programmable Gate Array (FPGA) as shown in Fig. 1(c). Tab. 1 gives a wavelength routing map between four racks within one cluster of a 4x4 racks OW-DCN. In particular, the SWS follows the wavelength routing map of the AWGR to activate or deactivate the corresponding SOA connected to the laser, enabling the ToR switch to communicate with the target ToRs via two parallel intra- and inter-cluster networks. These network units are interconnected by a group of full-duplex and high-capacity OW links. Two fundamental methods are utilized to realize these

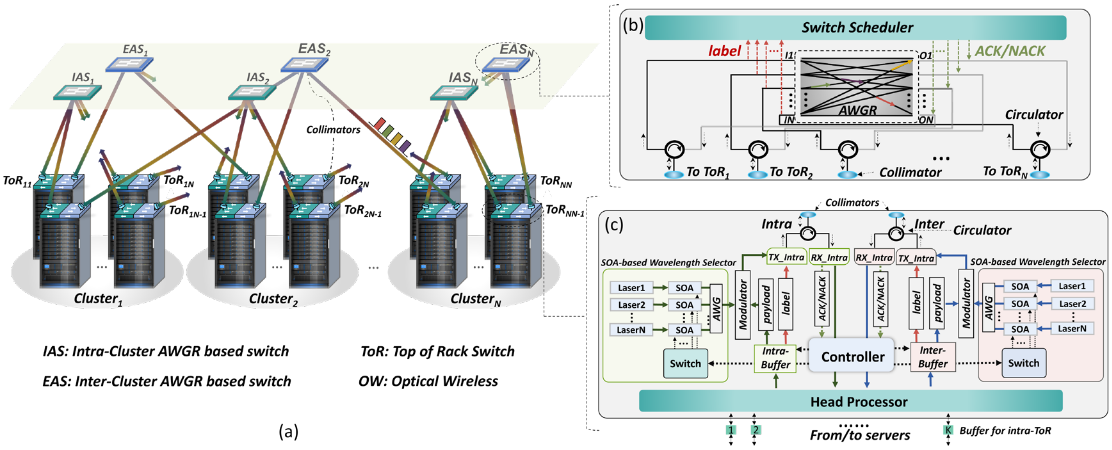

Fig. 1. (a) The schematic diagram of the OW-DCN architecture, (b) The functional blocks of the AWGR-based optical switch, (c) The functional blocks of SWS based ToR switch.

OW links. The first is the reversibility principle of optics, where a light beam follows the same path when reversed. Thus, only one beam steering device is required for bidirectional OW transmission. Second, the cost-effective PAM-4 modulation format has been employed to enable spectral efficient high-capacity transmission links. Specifically, the full-duplex and high-capacity OW system is a simple mechanism that is realized by utilizing optical circulators and collimators on the ToR switch and optical switch side. The collimators are employed to establish the OW wireless links, whereas the circulators are used to separate the transmitted and received optical signals based on the transmission direction. In this way, full-duplex and high-capacity links are established for intra-\inter-cluster communication networks. More details regarding the fast optical switching technology in the proposed OW-DCN, including packet switching strategy, contention methodology, and reconfiguration capability are presented and experimentally demonstrated in our prior work [11].

Tab. 1: Wavelength (in nm) routing map between four racks within one cluster of a 4x4 racks OW-DCN.

λ (nm)	O1 (ToR1)	O2 (ToR2)	I3 (ToR3)	I4 (ToR4)
I1 (ToR1)	1538.13 (λ_1)	1536.5 (λ_2)	1541.40 (λ_3)	1539.76 (λ_4)
I2 (ToR2)	1539.76 (λ_4)	1538.13 (λ_1)	1536.5 (λ_2)	1541.40 (λ_3)
I3 (ToR3)	1541.40 (λ_3)	1539.76 (λ_4)	1538.13 (λ_1)	1536.5 (λ_2)
I4 (ToR4)	1536.5 (λ_2)	1541.40 (λ_3)	1539.76 (λ_4)	1538.13 (λ_1)

Experimental Investigations and Discussions

To evaluate the performance of the proposed full-duplex, high-capacity OW transmission system based OW-DCN, a proof-of-concept experimental setup is constructed based on the interconnections of intra-cluster transmission between the four racks within one cluster of a 4×4 rack OW-DCN. Notably, inter-cluster communication functions similarly to intra-cluster communication. To examine the effect of worst-case crosstalk, the duplex transmission between ToR1 and ToR3, which uses the same wavelength (λ_3), is chosen based on the wavelength routing map in Tab. 1. In addition, three different transmission scenarios, namely half-duplex, full-duplex, and multicast transmissions, were conducted to compare the crosstalk and reflection introduced by duplex transmission.

Fig. 2 depicts the experimental setup. Two laser sources centred at λ_3 (1541.40nm) have been utilized to generate optical transmission signals for the duplex transmission between ToR1 and ToR3. Moreover, two additional optical channels centred at λ_4 (1539.46nm) were added for data transmitting from ToR1 to ToR4 and ToR3 to ToR2 in order to perform the multicast transmission scenario. The on/off status of the four channels is controlled by four SOAs. The combination of lasers and SOAs serves as a prototype of the SWS. Two 40GHz Mach-

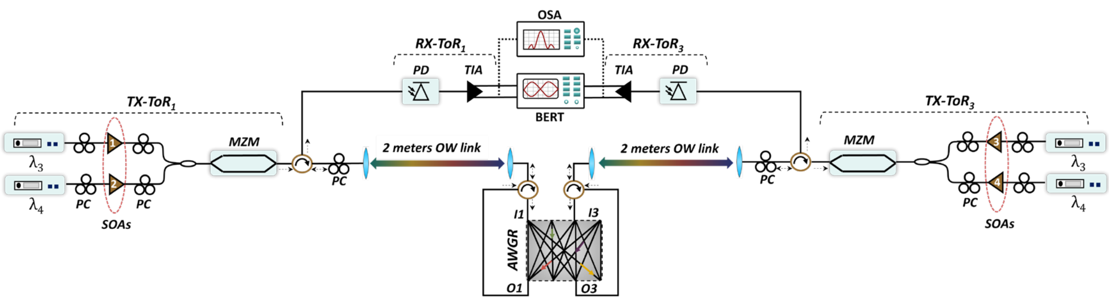

Fig. 2: The experimental setup to investigate the duplex transmission performance of the proposed OW-DCN system.

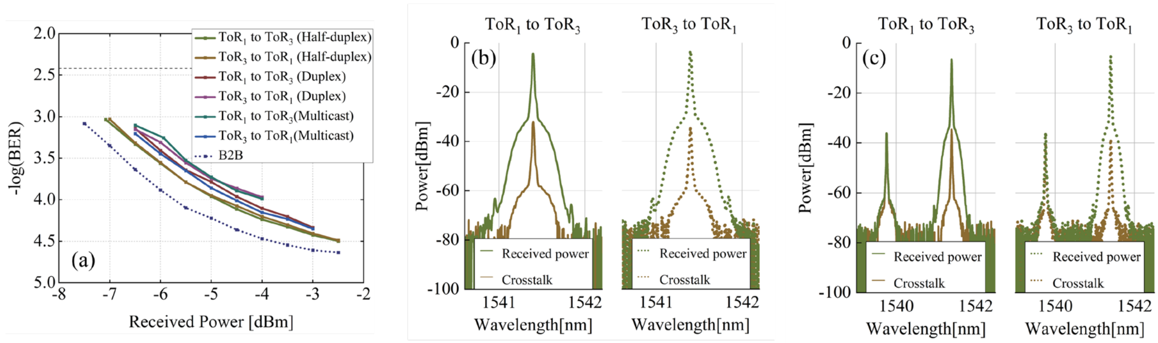

Fig. 3: (a) BER results with 56GBaud PAM-4 data, the captured spectrum for duplex (b) and multicast (c) transmission.

Zehnder modulators (MZM) are then employed to modulate the 56GBaud PAM-4 optical signals. The MZM is driven by two linear amplifiers (SHF D837C) with a 35GHz bandwidth. Gray coding is utilized to convert PRBS15 into PAM-4 symbols. Afterwards, two circulators are installed at the ToR side to separate the transmitted and received signals. While two additional circulators are installed at the AWGR, which served as the optical wavelength switch for routing the optical signals to their respective ToR receivers via two 2-meter OW links. Four Thorlabs TC18FC-1550 collimators are used to build the full-duplex optical wireless links. It should be noted that since a well-collimated, narrow optical light signal was employed, the wireless link length can be much longer. Moreover, polarization controllers are used to optimize the signal polarization states for the SWSs, MZMs, and optical switch. On the receiver side, a bit error rate tester (BERT) is used to evaluate the transmission quality, while an optical spectrum analyser (OSA) is used to measure the crosstalk (in-band and out-band) for the duplex transmission and multicast transmission scenarios.

First, the half-duplex transmission is evaluated by only biasing SOA1 to transmit the optical signal λ_3 from ToR1 to ToR3. Afterward, only SOA3 is biased to allow half-duplex transmission from ToR3 to ToR1. Regarding the evaluation of full-duplex transmission, both SOA1 and SOA3 are simultaneously enabled for duplex transmission between ToR1 and ToR3. Finally, the multicast transmission is carried out by activating all of the four SOAs in order to enable all four transmissions, which are the transmissions between ToR1 to both ToR2 and ToR3, and ToR3 to both ToR1 and ToR4. In addition, a back-to-back (B2B) measurement is conducted by connecting the output of the modulator to the input of the receiver with single-mode fibers.

Fig. 3(a) depicts experimental results. For each transmission scenario, a data rate of 112Gb/s below the FEC threshold of 3.84×10^{-3} has been achieved. The half-duplex transmission achieves a power penalty of less than 0.5dB compared to the reference B2B transmission. Regarding duplex transmission and multicast transmission, an approximately 1.5dB power penalty has been observed. In addition, all relevant spectra (illustrated in Fig. 3(b) and (c)) are captured for each transmission scenario in order to evaluate the crosstalk effect. A crosstalk of < -30dB has been observed for duplex transmission. In the multicast transmission scenario, both out-of-band and in-band noise are measured to be approximately -40dBm. This indicates that the proposed duplex OW system for the OW-DCN has minimum crosstalk between transmission links benefiting from the filtering capability of the AWGR-based optical switch. Furthermore, the transmission of multi-level modulation formats demonstrates the possibility of incorporating a complex modulation format into our proposed full-duplex OW system for OW-DCN once the required linearity at the transmitter and SNR levels at the receiver and are achieved.

Conclusions

A full-duplex and high-capacity optical wireless transmission system, supporting real-time 112Gb/s with bit error rates below FEC $3.84\text{x}10^{-3}$ using PAM-4 modulation, has been proposed and experimentally demonstrated for OW-DCNs. The experiment is conducted using a prototype of one cluster within a 4×4 racks OW-DCN. Multiple transmission scenarios, including half-duplex, full-duplex, and multicast transmission, are experimentally investigated. The power penalty observed is less than 0.5dB for half-duplex transmission, and approximately 1.5dB for full-duplex and multicast transmissions compared to B2B transmission. Additionally, both full-duplex and multicast transmission crosstalk is measured with the results of less than -30dB. The experimental demonstrated system at 112Gb/s PAM-4 is robust and deployable and thereby a promising solution for a high-capacity, full-duplex OW transmission system for OW-DCN.

Acknowledgement

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