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Elastic all-optical multi-hop interconnection in data centers with adaptive spectrum allocation

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ABSTRACT

In this paper, a novel flex-grid all-optical interconnect scheme that supports transparent multi-hop connections in data centers is proposed. An inter-rack all-optical multi-hop connection is realized with an optical loop employed at flex-grid wavelength selective switches (WSSs) in an intermediate rack rather than by relaying through optical-electric-optical (O-E-O) conversions. Compared with the conventional O-E-O based approach, the proposed all-optical scheme is able to off-load the traffic at intermediate racks, leading to a reduction of the power consumption and cost. The transmission performance of the proposed flex-grid multi-hop all-optical interconnect scheme with various modulation formats, including both coherently detected and directly detected approaches, are investigated by Monte-Carlo simulations. To enhance the spectrum efficiency (SE), number-of-hop adaptive bandwidth allocation is introduced. Numerical results show that the SE can be improved by up to 33.3% at 40 Gbps, and by up to 25% at 100 Gbps. The impact of parameters, such as targeted bit error rate (BER) level and insertion loss of components, on the transmission performance of the proposed approach are also explored. The results show that the maximum SE improvement of the adaptive approach over the non-adaptive one is enhanced with the decrease of the targeted BER levels and the component insertion loss.

1. Introduction

With a rapid growth of bandwidth-hungry applications, such as cloud-based services and high-definition video streaming, the capacity demand for data center networks that are responsible for the traffic within the data centers has been increasing sharply. In addition to high capacity, low energy consumption is another indispensable requirement of data centers for sustainable development, particularly for large-scale site infrastructure [1,2]. In this regard, many optical interconnect architectures have been proposed, which are able to offer much higher capacity and power efficiency than its electrical counterpart [3].

A typical data center network might contain several tires, e.g., edge, aggregation and core tiers [4]. The higher tier aggregates the traffic from the lower tiers, and therefore, demands more capacity. Optical approaches, such as [5–8], have been introduced in aggregation/core tier, which tackle with the traffic among racks (i.e., inter-rack connections) and also the ones from/to the Internet. Helios [5] and c-Through [6] are hybrid electrical and optical switch architectures, where the optical circuit switching (OCS) is introduced to handle the flows with high capacity demand (e.g., elephant flows). However, both of them are still confined by the electrical part for capacity upgrade and energy efficiency improvement. LIONS [7], an arrayed waveguide grating router (AWGR)-based low-latency interconnect using optical packet switching (OPS), and OSA [8] which is a purely OCS based architecture, are all-optical solutions which completely remove electrical switches. Due to the lack of proper optical buffering techniques, optical-electrical-optical (O-E-O) conversions are still needed in LIONS, which not only consume a huge amount of energy but also become the bottleneck for high capacity applications. As an OCS based architecture, OSA does not need buffering in the switch. However, a large optical switch matrix (OSM) is required in order to establish all-to-all connections among the racks, resulting in a scalability problem. In this regard, [8] introduced space switching, where the traffic experiences multiple hops before reaching the final destinations, so that direct all-to-all connections

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are not necessary and the total number of the ports required by the OSM in OSA can be significantly reduced. It should be noted that the multi-hop routing proposed in [8] is not transparent in optical domain, where the traffic undergoes O-E-O conversion in every hop. It may lead to congestion at the intermediate nodes (racks) and decrease the overall energy efficiency. To mitigate this problem, an all-optical multi-hop interconnection scheme was proposed in our previous work [9], which employs the optical loops at each rack to eliminate the O-E-O conversion during hopping. Meanwhile, the inter-rack flows in a data center network that aggregate the traffic from the rack can vary all the time [10], leading to dynamic traffic at core tier. An elastic spectrum allocation was introduced in [9] to improve spectrum utilization, where the number of spectral slots is assigned according to the varied inter-rack traffic demand. It is expected such a flex-grid approach can achieve higher spectrum efficiency compared to a fixed-grid scheme [11,12]. However, in [9], the optical channel bandwidth is allocated according to the worst case (i.e., the path with the largest number of hops), to alleviate the impact of transmission impairment, resulting in over-grant in spectrum allocation. Here, the path is referred to as the one from the source rack to the destination rack through single (not passing any intermediate rack) or several hops (passing at least one intermediate rack).

To enhance the spectrum efficiency (SE), in this paper we further extend transparent flex-grid multi-hop optical interconnection presented in our previous work [9] by introducing adaptive elastic spectrum allocation, where the various optical channel bandwidth is assigned according to the numbers of hops [13]. Furthermore, in this paper we concentrate on transmission performance and investigate the impact of modulation formats on the proposed optical interconnect architecture. Directly detected optical pulse amplitude modulation (DDO-PAM) is widely used in data center network [14] for its low complexity while its tolerance to the impairment is low, particularly for ultra-high data rates, in order to achieve sufficient transmission performance. To mitigate this problem in the core switch, coherently detected optical quadrature amplitude modulation (CO-QAM) is investigated as well. Though nowadays the coherent detection is still costly, the digital signal processing (DSP) in coherent receiver for intra-data center application can be largely reduced compared to that in the long-haul cases. For example, ~25% DSP effort is for chromatic dispersion (CD) compensation in long-haul transmission [15], while CD is negligible in the short-reach optical fiber links for the intra-data center network. Furthermore, the cost of coherent transceiver is expected to significantly decrease with the advances in chip integration [16]. Therefore, coherent detection can be a promising transmission technique for the data center applications as well. We measure bit error rates (BERs) under various modulation formats, including 4QAM/16QAM/64QAM/256QAM (CO-QAM) and DDO-2PAM (i.e., on-off keying OOK) for high data rates (i.e., 40 Gbps and 100 Gbps) by Monte-Carlo simulations. The results show that the adaptive elastic spectrum allocation approach can boost the SE by up to 33.3% at 40 Gbps and 25% at 100 Gbps, respectively. The impact of transmission parameters (e.g., targeted BER levels, insertion loss of components) on the proposed adaptive approach in terms of maximum allowable number of hops and SE/slotted SE improvement are also discussed.

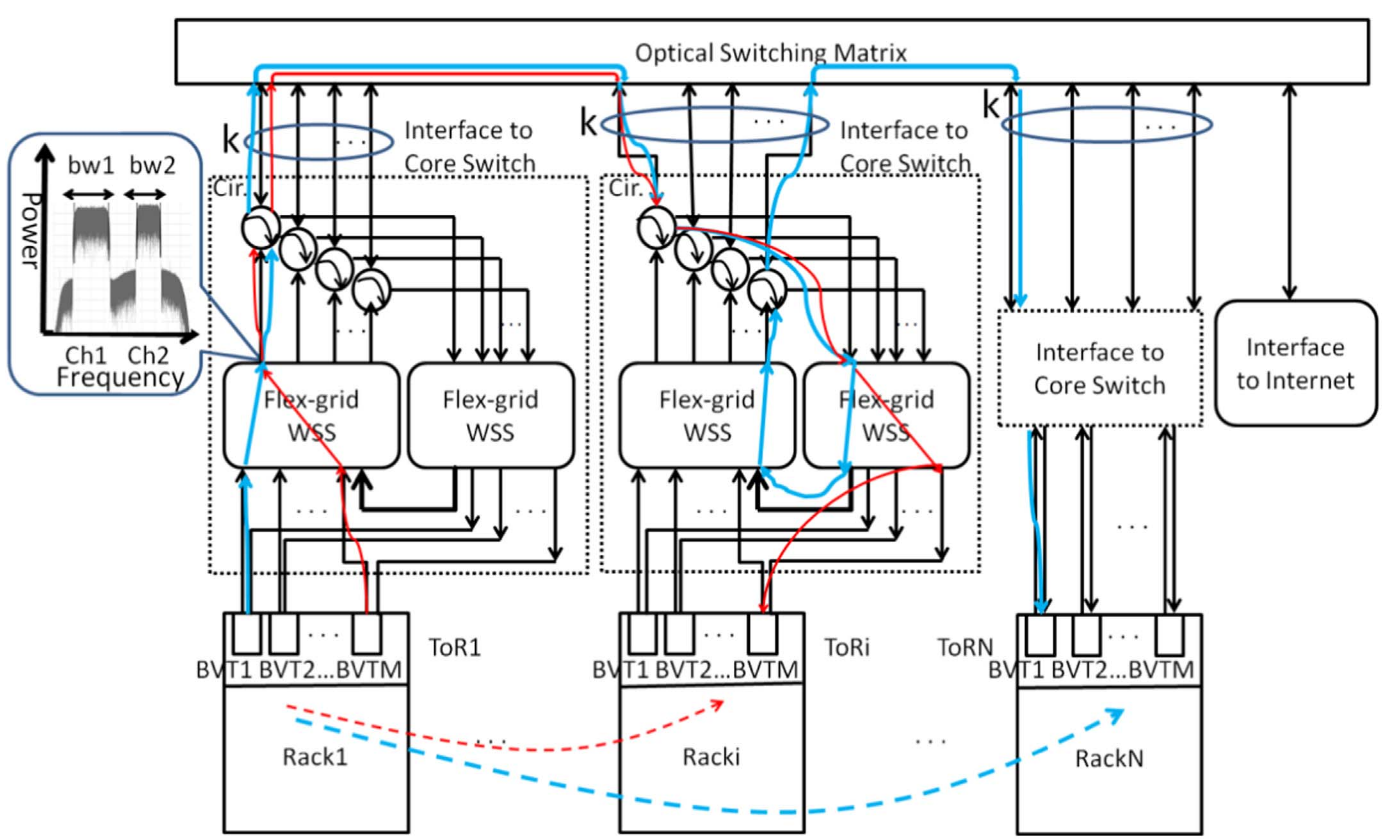

Fig. 1. Elastic all-optical interconnect supporting transparent multi-hop interconnections for inter-rack communications. (WSS: wavelength selective switch, ToR: top of rack, BVT: bandwidth variable transceiver. The red lines depict an example of a 1-hop connection between Rack 1 and Rack *i*, while the light blue lines show an example of a 2-hop connection between Rack 1 and Rack *N*. The dashed lines represent the connection requests and the solid lines represent the corresponding routing paths.). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).