Software Defined Elastic Optical Networks for Cloud Computing

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Abstract—This paper discusses prospects and challenges of software defined elastic optical networking for grid and cloud computing environments. We will exploit the OpenFlow based unified network control and management for both intra- and inter-datacenter networks embedded in the cloud. The intra-datacenter network is a fiber rich environment. Therefore we assume a flattened optical switching architecture using arrayed waveguide grating routers (AWGR) with fixed spectrum grid. For the inter-datacenter network, spectral resources are more precious between the distributed long-haul fiber connections. Therefore we assume elastic optical networks with flexible grid to achieve high spectral efficiency. This paper discusses the elasticity of the multi-datacenter cloud computing environment which includes both fixed-grid and flexi-grid optical networks, and introduces a unified, software defined network control plane based on OpenFlow technologies.

Index Terms—cloud computing, elastic optical networks, network control and management, software defined network, OpenFlow.

I. INTRODUCTION

ARGE-SCALE computing platforms (called data centers or warehouse-scale computing) that drive the information technology have significantly transformed our lives over the past decades. Cloud computing allows users to access such large computing platforms ubiquitously. In order to do this, the switching and networking infrastructure in support of cloud computing has to be scalable, agile, resilient, and pervasive. Further, many cloud computing applications now require high-throughput and low-latency. Since these applications must run end-to-end across many heterogeneous networks including datacenters and service providers, we must consider the issues of both intra-datacenter and inter-datacenter networking.

The intra datacenter network is a fiber-rich environment, where the fixed-grid optical network can be used by leveraging off-the-shelf optical components, e.g. fixed wavelength optical transponders, etc. The major challenge is to develop scalable, high-port count interconnection switches with the capability of supporting millions of nodes, while providing high throughput, low latency and resiliency.

On the other hand, the inter data-center network typically includes long-haul fiber transmissions since datacenters are geographically distributed in rural areas. We can leverage the legacy backbone network to deliver such high volume datacenter traffics. However, the exponential growth of bursty Internet traffic implies that we need to look beyond solutions based on wavelength division multiplexing (WDM) in fiber networks. Flexible-grid elastic optical networks (EON) [1] were recently proposed to achieve high spectral efficiency and adaptive networking with agile granularities of spectrum allocation beyond the rigid ITU-T spectrum grid (G.694.1) [2]. Therefore, the new challenges for the inter datacenter network may lie in intelligent spectral resource sharing methods between the datacenter traffic and diverse end-user traffics.

In light of different network architectures and resource management problems in intra- and inter-datacenter networks, an intelligent and unified control plane which can make the optimized use of the switching and transmission resources is strongly in demand. The GMPLS-based control plane has not been deployed in real operational networks, mainly due to its distributed nature and high complexity. On the other hand, the newly emerging OpenFlow control plane architecture offers flexibility for operators to directly control and manage a network. The OpenFlow-based network control and management is very suitable for grid or cloud applications, since OpenFlow is proposed as a framework for network operation systems, whereby the forwarding tables in switches and routers can be freely and fully programmed. By separating the control plane from the data plane, OpenFlow can program the entire networks, and can allow virtualization of IP routers, Ethernet switches or even optical switching nodes (e.g., wavelength selective switches (WSS), photonic cross connects (PXC), and optical burst/packet switches). Through the appropriate programming of the routers/switches, the network can be logically partitioned as separate virtual networks, where each virtual network can use its own set of protocols and policies to support different grid or cloud services. The flexibility brought by OpenFlow inspires a more general concept as software defined networking (SDN). As depicted in Fig. 1, our proposed SDN across multiple domains can rely on peering of multiple control and management systems, each administrating its own domain. In some cases, federation or aggregation will allow overlay or apparent convergence (for certain specific applications) of such control and management functions across multiple domains. These functions are separated from the underlying heterogeneous data plane network to provide the high-level resource abstractions and to enable agile and intelligent manipulation of such abstracted resources for various cloud computing applications. By leveraging SDN, cloud computing applications need not know the data plane network infrastructure, and can only treat them as a pool of bandwidth resources which are available as needed.

The remainder of the paper is organized as follows. Section II discusses Light Interconnect Optical Network Switches...
(LIONS) for intra-datacenter networking, where the AWGR with fixed spectral grid and tunable lasers are used as the switching fabric. The use of LIONS as a modularized building block with limited number of wavelengths to construct a flattened, scalable switching network is also discussed. Section III describes the flexible grid optical networking technologies for inter-datacenter long-haul data transmissions and switching, and also covers the integrated OpenFlow control plane for such elastic optical networks. Section IV reviews some of the recent testbed studies for both intra- and inter-datacenter networks. Section V concludes this paper.

II. LIGHT INTERCONNECT OPTICAL NETWORK SWITCHES FOR INTRA-DATACENTER NETWORKING

AWGR [3, 4] is a passive wavelength routing component that enables all-optical switching. The uniform-loss cyclic-frequency (ULCF) [3] feature of an \( N \times N \) AWGR supports simultaneous and non-blocking interconnections of each of \( N \) input ports with all of \( N \) output ports by using \( N \) wavelengths. Each input port can utilize a wavelength (instead of electronic headers) to address the output port. For this reason, any input port can use a tunable transmitter to address each output port by tuning the transmitter to the corresponding wavelength. When each output port is equipped with a wavelength demultiplexer and \( N \) receivers, the architecture is contention-less.

Figure 2 shows LIONS architecture, which includes optical channel adapters (OCA), tunable wavelength converters (TWC), loopback buffers and the control plane for the switching fabric. LIONS uses label switching with the optical label transmitted on a different wavelength [5]. The experimentally calibrated and validated simulation results prove a scalable LIONS switching architecture with high throughput and low average end-to-end latency [5].

Alternatively, the \( N \times N \) AWGR can provide all-to-all interconnection without contention by employing \( N \) transmitters and \( N \) receivers at each port. Therefore, compared to the directly connected all-to-all interconnection, the shuffling of the \( O(N^2) \) “optical wires” is confined to a single AWGR. However, despite the intrinsic merit of dense connectivity in AWGRs, their port count is usually restricted by the size, the fabrication constraints and the inter-channel crosstalk. The difficulties arise mainly from the required critical control on the channel spacing in fabrication as well as accurate wavelength registration for all channels after fabrication [6]. Moreover, in an \( N \times N \) single AWGR system, the signal-crosstalk beat noises accumulate among the \( N-1 \) components [4], which also limits \( N \) from being large. Therefore, the need arises for an all-to-all interconnection architecture using AWGRs with limited number of wavelengths.

The more favorable arrangement of LIONS will include many smaller AWGR with a fewer number of wavelengths to achieve the same all-to-all interconnection requirement in the original system with a single large AWGR. Fig. 3 shows such an example of interconnecting \( N \) nodes using \( W \) wavelengths and \( W \times W \) AWGRs. The transmitters for each processor consist of \( M \) (\( M=N/W \)) groups of \( W \) fixed lambda lasers, with each

![Figure 1. Software Defined Heterogeneous Network for Cloud Computing.](image)

![Figure 2. The system diagram of the proposed rack to rack LIONS optica switch.](image)
group connected to a separate AWGR input port using a distinguished waveguide. Note that the number of wavelengths used in the system is reduced by a factor of $N/W$, while the total number of ports in all the AWGRs increases by a factor of $N/W$ in return. Eventually, in an $N \times N$ all-to-all system with $W$ wavelengths, a total number of $N^2/W$ ports are required. The number of optical wires is determined by the number of total connected ports on the AWGRs, which is $2N^2/W$. Therefore, compared with the $N(N-1)$ wires using direct connection, the use of $W$ wavelengths in parallel allows for reducing the optical wiring by a factor of $W(N-1)/2N$.

The $N \times N$ AWGR based all-to-all interconnection architecture does not require a control plane, since no contention can occur between the nodes. However, this would require each node to be equipped with $N^2$ transmitters and $N$ receivers simultaneously, so that total of $N^2$ transmitters and $N^2$ receivers in the interconnection network. Reducing this to a more realistic design can involve reducing the transceivers to a smaller number (2–4) per node at the expense of incurring modest contention probability [7].

Therefore, an intelligent control plane technique for LIONS should not only handle the contentions inside a switch, but also coordinates with other switches’ control planes. OpenFlow enabled optical switch architecture provides us an opportunity of constructing such control plane.

Fig. 4 shows the framework of OpenFlow enabled LIONS. In order to control this node through the OpenFlow protocol, we introduce virtual Ethernet interfaces (veths) to an OpenFlow switch. These veths are virtualized from the physical interfaces of the LIONS and each veth exactly corresponds to a physical interface of the LIONS. By using this approach, the virtual OpenFlow switch obtains a virtualized view of the physical structure of the LIONS, which greatly benefits the NOX in controlling the cross-connections within the LIONS by using the OpenFlow protocol. For simplicity, this virtual OpenFlow switch is referred to as the OpenFlow agent.

Once a request/flow is received by the NOX, the NOX obtains the source and destination IP addresses of this flow and then performs routing algorithms based on its knowledge of the whole network. After that, according to the results, the NOX inserts a new flow entry in the flow table of the OpenFlow agent. In turn, based on the flow entry, the OpenFlow agent automatically sends control commands to cross-connect the corresponding ports of LIONS, thanks to the same virtualized view of the LIONS structure in the OpenFlow agent.

III. FLEXIBLE GRID OPTICAL NETWORKING TECHNOLOGIES FOR INTER-DATACENTER COMMUNICATIONS

As discussed earlier, the inter-datacenter communication benefits from an elastic and flexible control and management of the limited spectrum resources in the optical backbone network. The recently proposed flexible bandwidth elastic optical networking technologies [2] have the capability of provisioning both subwavelength and superwavelength channels with arbitrary bandwidth according to the user demands. Since flexible bandwidth networking requires the ability to generate arbitrary bandwidth flexpaths, the physical layer must employ a flexible bandwidth technology scalable beyond terahertz bandwidths. Multicarrier solutions such as coherent wavelength division multiplexing (CoWDM) and orthogonal frequency division multiplexing (OFDM) have been proposed as possible physical layer solutions for flexible bandwidth networking. These solutions rely on the generation of many low-speed subcarriers to form broadband data waveforms. CoWDM maintains orthogonality between closely packed subcarriers by individually modulating a set of coherent subcarrier tones, while OFDM maintains orthogonality between subcarriers using inverse Fourier transform at the transmitter and Fourier transform at the receiver. Both CoWDM and OFDM systems can change the modulation format of individual subcarriers, but lack the ability to arbitrary control the subcarrier symbol rate and spacing with a single physical architecture.

A more general method for flexible broadband waveform generation is called dynamic optical arbitrary waveform generation (OAWG) and measurement (OAWM) [8-10]. It can generate data waveforms in both single carrier modulation formats and multicarrier modulation formats such as CoWDM and OFDM. Also, in contrast to multi-carrier systems, OAWG utilizes the parallel synthesis and coherent combination of many lower bandwidth spectral slices to create broadband waveforms, hence the spectral slice bandwidth is not related to the subcarrier bandwidth of generated waveforms. This removes any restrictions on the subcarrier bandwidth and its modulation format. Further, the parallel nature of OAWG
enables bandwidth scalability (> 1 THz) without increasing the bandwidth requirement on the supporting electronics.

Dynamic OAWG begins with a coherent optical frequency comb (OFC), which is spectrally demultiplexed with narrow passband AWG placing each comb line at a separate spatial location. A set of in-phase and quadrature-phase modulators (I/Q modulators), each with a bandwidth of \( \Delta f_o \), applies temporal I/Q modulations to broaden the comb lines to create the spectral slices. Coherently combining the spectral slices using a gapless spectral multiplexer with broad overlapping passbands ensures a continuous bandwidth output waveform. At the receiver side, a complementary technology called optical arbitrary waveform measurement (OAWM) is used to detect the waveform. It divides the broadband continuous waveform into many spectral slices for parallel measurement using independent digital coherent receivers.

In DWDM networks, the wavelength bit rate, the optical reach, and the spectrum are all fixed. Hence, a certain demand can occupy less than a full wavelength, resulting in the wasted capacity, as demand C in Fig. 5(c), or wasted guard-bands when using more than one wavelength, as in Fig. 5(a). EON allows for multiple choices when implementing a demand: the modulation format can be assigned to a given demand according to its reach distance, in such a way the spectral bandwidth occupied by the optical path can be minimized, as demands \( D \) and \( E \) depicted in Fig. 5(d). “Super-channels” can be constructed if the demand is too large to be handled by a single optical channel. A super-channel contains multiple very closely spaced channels, which traverse the network as a single entity, but can be demultiplexed at the receiver. Fig. 5(b) illustrates that the super-channel in EON occupy less spectral resources compared to the fixed network case shown in Fig. 5(a).

The OpenFlow-based control plane for EON, referred to as OpenSlice, has been firstly proposed in [11]. As Fig. 6 indicates, OpenSlice introduces a cross-connection table similar to the flow table in standard OpenFlow, which maintains all the cross-connection information within a bandwidth variable wavelength cross-connect (BV-WXC), including input/output ports, central frequency, slot width, and modulation format.

![Diagram](image_url)

**Figure 5** (a) Fixed grid maintains strict guard bands between optical paths that implement a 3x40Gb/s demand; (b) The 120Gb/s demand can be groups tightly into a superchannel and transported as one entity; (c) five demands and their spectrum needs on a fixed grid network, assuming QPSK modulation; (d) the same demands, with adaptive modulation optimized for the required bitrate and reach; (e) the same demands, with flexible spectrum grid.

**Figure 6** A cross-connection entry in the cross-connection table.

The Slice Mod message, which is extended from the standard Flow Mod message, can add/delete a cross-connection entry into the cross-connection table, and thus control the BV-WXC, allocating a cross-connection with the appropriate spectrum bandwidth to create an appropriately-sized optical path.

### IV. TESTBED STUDIES

The elastic optical network can realize impairment-aware networking [12] when equipped with a real-time optical performance monitoring and an adaptive control plane to optimize the routing and resource allocation according to the monitored impairments. By adopting a spread-spectrum real-time performance monitoring method that covers a broad and adjustable bandwidth [13], the network can dynamically and adaptively adjust the modulation format to maximize spectral efficiency while maintaining the required quality of service (QoS) even when coped with time-varying physical layer impairments (PLIs). In a recent testbed demonstration, we utilized a supervisory channel with low speed (e.g. 1.25 Gb/s) encoding with low modulation index (e.g. ~ 0.1) on top of the relatively broad data spectrum. Since the data and the supervisory channel signal follow that same path, the bit-error-rate BER of the data is strongly correlated with that of the supervisory channel. The correlation between the measured BERs for the supervisory channel versus the data channel for three data modulation formats: BPSK, QPSK, and 8PSK was plotted [14]. The strong correlation indicates that the BER of the supervisory channel can be used to estimate the BER of the data at different modulation format, or to choose the modulation format that maximize the spectral bandwidth while meeting the QoS requirement (in this case, data BER < 1E-4).

By incorporating this supervisory channel BER measurement in the control plane distributed over the network, one can map the link state condition across the network, and adjust the modulation format. Paper [14] shows a result of such an automated and real-time control plane, where the control plane maintains acceptable BER (< 1E-4) under a time-varying impairments inducing variations in optical signal to noise ratio (OSNR). The network testbed automatically adjusted the modulation format from 8PSK to QPSK and to BPSK to maintain BER < 1E-4 as OSNR decreased; as OSNR increased, the modulation format changed back from BPSK to QPSK and then to 8PSK to maximize spectral efficiency [12].

In [11], we successfully demonstrated OpenSlice, an OpenFlow-based control plane for spectrum sliced elastic optical path networks. We experimentally verified its overall feasibility for dynamic end-to-end path provisioning and IP traffic offloading through OpenFlow-based protocol extensions and seamless interworking operations. We also quantitatively...
evaluated its performance in terms of path provisioning latency, and compared it with the GMPLS-based control plane. The results indicate that, in our tested scenario, the OpenSlice outperforms the GMPLS-based control plane when creating an elastic optical path with more than 3 hops. In [15], a first field trial of OpenSlice has been successfully carried out, which further validated the efficiency of the OpenSlice for EON control. The paper demonstrated an extended OpenFlow based control plane allowing seamless operation across heterogeneous state-of-the-art optical and packet domains. It also demonstrated multi-domain network slicing and verified results on a global scale trial involving test-beds in UK, Spain and Japan.

V. CONCLUSION

This paper discusses software defined elastic optical networking for cloud computing. The cloud computing systems include not only datacenters and large-scale computing platforms, but also heterogeneous and multi-domain network infrastructures that interconnect them inside and outside. In intra-datacenter networks, LIIONS utilizes the AWGR to support high-throughput and low-latency interconnection while leading to a flattened topology with scalability. OpenFlow enabled LIIONS can greatly benefit from the unified control plane for the intra-datacenter networks. In inter-datacenter networks, the flexible grid elastic optical networking technologies can support improved spectral efficiency and better accommodates bursty data traffic. The OpenFlow-based control plane for EON, referred to as OpenSlice, has shown the validated efficiency and feasibility through field trial experiments. Overall, the OpenFlow-based software defined networking offers an intelligent and unified control plane that facilitates optimized utilization of switching and transport resources in intra- and inter-datacenter networks.

REFERENCES


Biographies:

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