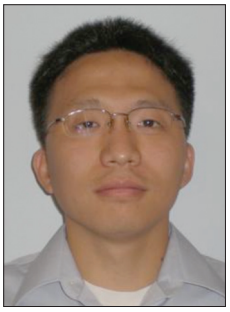
Optical Networks in Cloud Computing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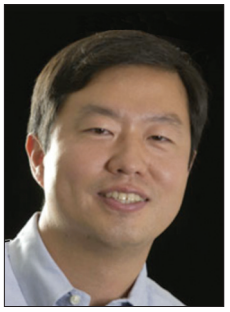
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Recent advances in cloud computing suggest that convenient and prompt access to distributed and powerful computing and networking resources is critical for provisioning high-quality services for data-intensive applications. Hence, we have to facilitate efficient interworking of the computing, networking, and storage resources in networks for cloud services. Optical networking technology can play an important role in realizing cost-effective interconnection of a wide variety of resources over a highly distributed computing environment, especially when the cloud solution has to address massive data exchange and processing.

In order to facilitate flexible access to the numerous bandwidths of optical fiber, researchers have developed a few promising technologies. These ongoing efforts indicate that agile and automatic bandwidth provisioning can be realized. For physical transmission, mixed line rate (MLR) and optical orthogonal frequency-division multiplexing (O-OFDM) have been investigated for supporting sub-wavelength bandwidth allocation granularity. In terms of optical switching, optical packet/label/burst switching technologies have been proposed to fill the gap between optical bandwidth and client demands. These proposals can make optical bandwidth allocation and switching adapt to the spatial and temporal nature of cloud traffic. Additionally, since the backplanes of supercomputers and switches/routers have become one of the primary bottlenecks to data transfer within data centers, optical interconnecting within data centers can facilitate the seamless convergence of cloud computing and optical networks.

The purpose of this Special Issue is to explore the recent advances in optical networking technologies for cloud computing, including different levels of design and development, from the device level to the system and network levels. We were pleased to receive 22 submissions from which seven articles were accepted for this Special Issue, and brief summaries of the accepted articles are listed below.

"Advanced Modulation Formats for Short Reach Optical Communication Systems" by Tao *et al.* discusses the advanced optical modulation formats that are keys to high-speed data transmission for short-reach optical interconnects within data centers. The authors show that with these modulation formats, high-speed data transmission can be realized with low-cost optics. A number of promising modulation formats are reviewed, and their implementations in future short-reach systems are also discussed.

"All-Optical Packet/Circuit Switching-Based Data Center Network for Enhanced Scalability, Latency, and Throughput" by Perelló *et al.* proposes the LIGHTNESS data center network (DCN) architecture, which leverages a hybrid optical data plane that includes optical packet switching (OPS) and optical circuit switching (OCS) switching paradigms for server-to-server interconnection. On top of this hybrid OCS/OPS data plane, a DCN control plane based on software defined networking (SDN) technology is deployed. The overall DCN architecture enables data center operators to provision their services with flexibility, manageability, and customizability.

"Cross-Stratum Orchestration and Flexgrid Optical Networks for Datacenter Federations" by Velasco *et al.* discusses how to interconnect data centers with a flexible grid optical network whose control plane is based on the SDN architecture. In order to utilize the optical spectral resources more wisely, the authors propose to adjust the amount of spectral resources assigned to each lightpath connection dynamically.

"A Feasible Solution to Provide Cloud Computing over Optical Networks" by Taheri *et al.* proposes an infrastructure as a service (IaaS) architecture that incorporates the physical resources in the passive optical network (PON) optical line terminals (OLTs) and optical network units (ONUs) to enable the delivery of cloud services to end users over PONs.

"Greening the Cloud Using Renewable-Energy-Aware Service Migration" by Mandal *et al.* shows that flexible cloud operation techniques can facilitate the increase of renewable energy utilization in cloud systems. Specifically,

the distribution of loads on a cloud infrastructure can be (re)adapted according to the availabilities of renewable energies. Simulation results from a U.S.-wide cloud network infrastructure indicate that by using migration techniques, they can replace up to 30 percent non-renewable energies with renewable ones and thereby achieve significant reduction of carbon footprint.

"On Advantages of Elastic Optical Networks for Provisioning of Cloud Computing Traffic" by Klinkowski *et al.* investigates potential advantages of the deployment of elastic optical networking technologies in transport networks to serve cloud computing traffic. The discussion is supported by evaluation results obtained for pan-European and U.S. backbone networks from 2012 to 2020 using Cisco traffic predictions.

"Virtual Network Planning for Converged Optical and Data Centers: Ideas and Challenges" by Hou *et al.* proposes a virtual network planning method with the consideration of evolving recovery during power outages. Under this scenario, the authors investigate the integration of traffic grooming and server consolidation to improve the utilization of link bandwidth and servers. Meanwhile, anycast-based resource balancing is utilized to reconfigure the virtual networks for accommodating more service requests.

We would like to thank all the authors who submitted their work to this Special Issue. As Guest Editors, we want to express our appreciation to all the reviewers who dedicated their time and effort to help ensure the high quality of this Special Issue. Also, we have to thank Prof. Sherman Shen, the Editor-in-Chief, for his kind support and guidance. Finally, we hope that this Special Issue can serve as a useful reference for readers from both academia and industry, and will identify potential research directions for innovations in this area.

Biographies

ZUQING ZHU [SM'12] (zqzhu@ieee.org) received his Ph.D. degree from the Department of Electrical and Computer Engineering, University of California at Davis (UCDavis), in 2007. From July 2007 to January 2011, he worked in the Service Provider Technology Group of Cisco Systems, San Jose, California, as a senior R&D engineer. In January 2011, he joined the University of Science and Technology of China (USTC), where he currently is an associate professor. His research interests are elastic optical networks and energy-efficient optical networks. He has published more than 100 papers in peer-reviewed journals and conferences of IEEE, IET, and OSA. He has been on the Technical Program Committees (TPCs) of INFOCOM, ICC, GLOBECOM, ICCCN, and others. He is also an Editorial Board member of the Elsevier *Journal of Optical Switching and Networking*, Springer *Telecommunication Systems Journal*, Wiley *European Transactions on Emerging Telecommunications Technologies*, among others. He received the Best Paper Award from ICC2013. He is a Senior Member of OSA.

S. J. BEN YOO [F'07] (sbyoo@ucdavis.edu) received his B.S. degree in electrical engineering (with distinction), M.S. degree in electrical engineering, and Ph.D. degree in electrical engineering with a minor in physics, all from Stanford University, California, in 1984, 1986, and 1991, respectively. He currently serves as a professor of electrical engineering at UC Davis. His research at UC Davis includes RF-photonic devices, systems, and networking technologies for the future generation Internet and computing systems. In particular, he is conducting research on architectures, systems integration, and network experiments related to all-optical label switching routers, terahertz optical arbitrary waveform generation, flexible bandwidth networking, and optical interconnect technologies. Prior to joining UC Davis in 1999, he was a senior research scientist at Bell Communications Research, leading technical efforts in optical networking research and systems integration. He is a Fellow of the IEEE Photonics Society, a Fellow of the Optical Society of America (OSA), and a member of Tau Beta Pi. He is a recipient of the DARPA Award for Sustained Excellence in 1997, the Bellcore CEO Award in 1998, the Outstanding Mid-Career Research Faculty Award (UC Davis) in 2004, and the Outstanding Senior Research Faculty Award (UC Davis) in 2011. He also served as an Associate Editor for *IEEE Photonics Technology Letters*, a Guest Editor for *IEEE/OSA Journal of Lightwave Technology*, and *IEEE Journal of Selected Topics in Quantum Electronics*, and General Co-Chair for the Photonics in Switching Conference 2007, 2010, and 2012.

ZHAOHUI LI [M] (tlzh88@jnu.edu.cn) obtained his B.S. from the Department of Physics and M.Sc. from the Institute of Modern Optics from Nankai University, China, in 1999 and 2002, respectively, and his Ph.D. from Nanyang Technological University 2007. He joined the institute of Photonics Technology, Jinan University, China, as a professor in 2009. His research interests are optical communication systems, optical signal processing technology, and ultra-fine measurement systems. He has over 100 publications in internationally refereed conferences and journals.

NICOLAS FONTAINE [M] (nicolas.fontaine@alcatel-lucent.com) obtained his Ph.D. in 2010 from UC Davis's Next Generation Network Systems Laboratory (http://sierra.ece.ucdavis.edu) in electrical engineering. In his dissertation he studied how to generate and measure the amplitude and phase of broadband optical waveforms in many narrowband spectral slices. Since June 2011, he has been a member of the technical staff at Bell Laboratories at Crawford Hill, New Jersey in the advanced photonics division. At Bell Labs, he develops devices for space-division multiplexing in multi-core and few-mode fibers, builds wavelength crossconnects and filtering devices, and works on spectral slice coherent receivers.