School of Arts and Sciences
La Salle University

Towards a SLICE-enabled Future Internet

Yang Wang, Assistant Professor of Computer Science
Zachary McNulty, Computer Science and Mathematics Dual Major
(Class of 2018)

CONTENTS

I. Faculty Name and Department

Yang Wang, Department of Mathematics and Computer Science

II. Student Name

Zachary McNulty

III. Research Project Description

The last decade witnesses an explosive growth of the Internet traffic, driven by emerging applications such as *YouTube*, *Hulu*, and Cloud computing. The resulting global Internet traffic is expected to climb with a compound annual growth rate of 23% [1]. It is predicted that an individual will need to spend over 5 million years to watch the amount of video that crosses the Internet each month in 2019 [1]. This traffic explosion not only calls for bandwidth-abundant transmission technology, but also leads to huge power consumption [2]. For example, the worldwide data centers of *Google* continuously draw up to 260 million watts to support the *Google* search [3].

One stone to kill both "birds" is the spectrum-sliced elastic optical path (SLICE) network [4]. On the one hand, SLICE networks can provide abundant bandwidth due to the fine spectrum management. On the other hand, SLICE networks share the merit of low power consumption of optical networking and present new opportunities for the energy saving. In this following, we first discuss two major goals of our project: bandwidth-efficient SLICE networks, and energy-efficient SLICE networks. Finally, we discuss another dimension of study that will be explored based on the first two goals.

A. Efficiently Utilizing the Abundant Bandwidth in SLICE Networks

1) Why the SLICE Network is Bandwidth-abundant: The bandwidth advantage of SLICE networks can be shown through a comparison with the state-of-the-art optical WDM networks. Figure 1(a), 1(b) shows the spectrum management in WDM, and SLICE networks, respectively. The smallest granularity for carrying user's request is *sub-carrier* (e.g., S_1) in SLICE networks, which has a smaller capacity than the counterpart *wavelength* (e.g., λ_1) in WDM networks. Assuming that each sub-carrier is 10 GHz, and each wavelength is 50 GHz. When a user request size (say 20 GHz) is less than the size of a wavelength, one wavelength is assigned in WDM networks to accommodated the request while most spectrum resources (i.e., 30 GHz) are wasted. In SLICE networks, two sub-carriers can accommodate the same request without wasting the bandwidth. Moreover, wavelengths in WDM networks are separated from neighbors by the reserved guard-band frequencies to avoid the interference. In contrast, sub-carriers of SLICE networks, enabled by OFDM (Orthogonal Frequency Division Multiplexing) technologies, can overlap with the neighboring sub-carriers (without guard-band).
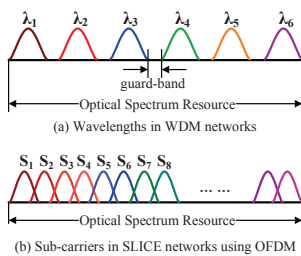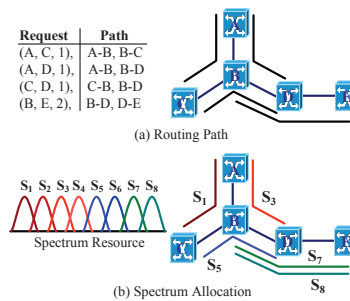

Fig. 1.   Spectrum Management
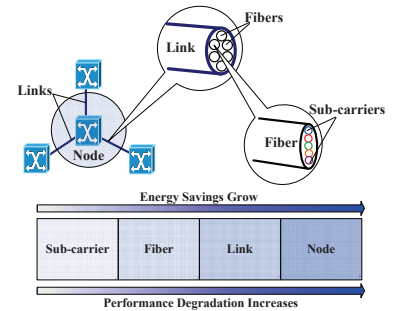

Fig. 2.   RSA

Fig. 3.   Energy Saving Spectrum

2) How to Efficiently Utilize the SLICE Bandwidth: To utilize the SLICE bandwidth for accommodating user requests, one has to employ the *Routing and Spectrum Allocation (RSA)* process. *Routing* refers to the path decision on how to transit the user request from the source to the destination. The *spectrum allocation* refers to the assignment of sub-carriers on each hop of the path. The challenge of RSA problem comes from three constraints: the *spectrum continuity*, *spectrum consecutiveness*, and *guard-carrier* constraints. We show the tip of the iceberg via an example in Fig. 2, where 5 nodes in a SLICE network are connected by 4 optical fibers, with 8 sub-carriers per fiber. User requests are given as a triple (s, d, v), where s, d are the source, destination node-pair, and v is the size of the request in terms of number of sub-carriers. The routing decision is given in Fig. 2(a) for each request. Figure 2(b) shows the spectrum allocation for satisfying each request. For example, S_1 is assigned along the path of node-pair (A, C) (i.e., A-B and B-C). We note that the sub-carrier(s) assigned along each path must employ the same sub-carrier (i.e., same color) to satisfy the *spectrum continuity* constraint. The *spectrum consecutiveness* requires that the set of sub-carriers that a request uses are consecutive in terms of the index. Thus the node-pair (B, E) uses two consecutive sub-carriers S_7 and S_8. The *guard-carrier* constraint explains why S_2, S_4, S_6 are unused since when paths of two requests overlap, sub-carriers of these two requests have to be separated by one or more unused sub-carriers.

The RSA problem can be shown to be an *NP-Complete* problem [5] (i.e., a type of problem that no *practical* optimal solution can be found for large instances). In the past, we have developed optimal model for the RSA problem using link-based Integer Linear Programming (ILP) formulations, which can resolve small or medium size RSA using ILP solver such as CPLEX [6]. In this project, we plan to develop alternative models (e.g., path-based) to reduce the computational time of our prior model, and explore time-efficient approximation algorithms for large-scale problems. Particulary, we are looking at a solution based on Lagrange Relaxation approach, which can bound the performance within a given ratio of the optimal solution with reduced computational time.

B. Exploring Energy Efficacy in SLICE Networks

1) Why the SLICE Network is Energy-efficient: In the literature, one common way to achieve energy savings is to turn off idle components [7]. For example, when a network interface card has no traffic flow, it can be turned off along with all the input/output ports of the card. SLICE networks bear a few inherent advantages in energy savings. First, the optical signal in SLICE networks (thanks to OFDM technologies) is robust against impairment. As a result, less signal re-generation needs to be done, which is one major source of power consumption in optical networks. Second, given the fine granular of sub-carrier in SLICE networks, there are more opportunities of turning off individual sub-carriers than wavelengths.

2) How to Achieve Energy Savings in SLICE Networks: In this past, we have proposed a concept, namely **Energy Saving Spectrum**, which consists of different granularities of components that can be turned off in SLICE networks. As shown in Fig. 3, an optical network consists of optical nodes and links. Optical links consists of optical fibers, which further contains a group sub-carriers. In this project, we plan to incorporate this concept to develop an energy-ware RSA process. To embed the *Energy Saving Spectrum*, our approach visualizes the SLICE network as a *Capacity Flow Network*, in which sub-carrier(s), fiber(s), link(s), and node(s) as well as the associated per-unit cost are all accessible. We plan to explore the energy savings at different granularities employing different strategies. For example, turning off the *sub-carrier* can be achieved by considering the user's time-dependent traffic demands, and enforcing the traffic sharing between users. And the *fiber/link/node* level turning-off can be achieved with a smart routing algorithm that purposely prevents the fiber/node/link from processing traffic.

C. Virtualization of SLICE Networks

The IT industry is stepping into an era of virtualization where computation, software, platform, infrastructure, (or any utility), are abstracted as logical services that can be delivered to the user in an elastic, agile, and automated manner (e.g., Cloud Computing). Virtualized SLICE networks can provide automated elastic high-capacity connectivity to the future Internet. However, to achieve this goal, one has to resolve the virtual network embedding (VNE) problem (i.e., an NP-Complete problem that has been explored in our prior summer research) along with the RSA problem. In this project, we plan to combine our previous results into the exploration of the RSA + VNE problem.

Overall, this project aims to investigate three challenging problems: the RSA problem, that decides how optical spectrum can be efficiently allocated in SLICE networks; energy-aware RSA which decides how to achieve RSA while taking energy savings as an extra dimension of complexity; and RSA+VNE that resolves RSA in virtualized SLICE networks. When combined, the proposed studies are expected to found a basis to enable a bandwidth-efficient and energy-efficient virtualized future Internet.

REFERENCES

[1] "Cisco Visual Networking Index: Forecast and Methodology, 2014 to 2019," http://www.cisco.com/.
[2] R. S. Tucker, R. Parthiban, J. Baliga, K. Hinton, R. W.A.Ayre, and W. V.Sorin, "Evolution of WDM optical IP networks: A cost and energy perspective," *IEEE Journal of Lightwave Technology*, vol. 27, no. 3, pp. 243–252, 2009.
[3] J. Glanz, "Google details, and defends, its use of electricity," in *The New York Times*, Sep. 2011.
[4] M. Jinno, Y. Tsukishima, H. Takara, B. Kozichi, Y. Sone, and T. Sakano, "Virtualized optical network (VON) for future Internet and applications," *IEICE Transactions Communications Magazine*, vol. E93-B, pp. 470–477, 2010.
[5] M. Garey and D. Johnson, *Computers and Intractability: A Guide to the Theory of NP-Completeness*. New York: W.H. Freeman, 1979.
[6] "CPLEX," http://www-01.ibm.com/software/integration/optimization/cplex-optimizer/.
[7] S. Nedevschi, L. Popa, G. Lannaccone, and D. Wetherall, "Reducing network energy consumption via sleeping and rate-adaptation," in *5th USENIX Symposium on Networked Systems Design and Implementation*, 2008, pp. 323–336.

IV. STUDENT RESEARCH COMPONENT

A. Role of Student in Project

Through this project, the student is expected to train and sharpen the following abilities. First, the ability to efficiently review the literature study associated with the research topic. Second, for networking research, the ability to combine and apply the major methodologies with creative ideas of their own. Third, the ability to evaluate networking protocols/algorithms via simulations, experiments, and analyses. Fourth, the ability to professionally present research findings. Fifth, the ability to effectively work as a team. Sixth, the ability to review other's work and provide critical comments.

Motivated by the above goals, students will be assigned guided tasks in different phases of the project. In the initial literature review phase, Zachary is assigned important recent publications, and is asked to write summary for each paper after reading.

To share my experience in network research, we will have a few group meetings to discuss major networking research methodologies, and evaluation approaches. Following that, in the problem solving stage, guided tasks will be given to Zachary to apply the methodologies to a specific aspect of our challenges, and further to a more general setting with gradually increased complexity.

As a preparation for the evaluation phase, I have continuously enrolled into the IBM Academic Initiative Program, and installed the cutting-edge *IBM CPLEX* Optimization tools. Zachary is currently installing this tool and plan to familiarize with it through some tutorials.

During the final stage, Zachary will prepare to present our work in both written and spoken forms. He will use professional editing tools such as *LaTex*, and plotting tools such as *GnuPlot*, to prepare an *IEEE* format technical report/paper. This report/paper is expected to summarize the surveyed literature, major contributions, detailed solutions, evaluation approaches and results, as well as major conclusions in a professional manner. Likewise, I will provide guidance to help Zachary prepare a version of the project report in spoken form with supporting *PowerPoint* slides.

As I am a regular reviewer for many journals and conferences, during above process, as I did in the Summer Research 2014, I will assign manuscripts to Zachary to review whenever possible. Also, including other two students that are currently voluntarily working with me in undergraduate research, we plan to hold regular group meeting and stimulate collaboration and cooperation via brainstorming discussion on addressing specific challenges.

Zachary in one of the best students in the department with strong self-learning skills, enthusiasm, and dedication for networking research. As a double major, he possesses both skills in mathematics and computer science to work on this project. Instead of being solely driven by me, we are all confident that this project will be an exciting joint collaboration and cooperation.

B. Student Authored Statement of Interest

"As a motivated dual major in Mathematics and Computer Science I am naturally excited to embark on a project that will not only be challenging, but also a great learning experience. I wish to gain more knowledge as well as experience in the fields of networking, modeling, and programming. I am excited to learn skills that this project will teach me, including: critical thinking and creative problem solving, optimization technologies in network research, and mathematical modelling of networks and programming." – *Zachary*

V. SUMMER WORK COMMITMENTS

A. Faculty

I will not teach classes in Summer 2016. As I did in Summer 2014, I will devote most of my time on this project. The detailed commitment can be found in the section below.

B. Student

Zachary is not taking summer classes, and are willing to devote all of their summer study efforts to this project. His detailed time commitments are shown in the section below.

VI. EXISTING SUMMER RESEARCH SUPPORT

None.

VII. FACULTY AND STUDENT TIME COMMITMENTS

Zachary has voluntarily worked with me since Fall 2015 through the CSIT 290 Introduction to Data Structures class. He has been prepared with basic background on the state-of-the-art networking research. There will be no lead time to start a comprehensive research with dedicated focus during the summer.

I will spend a minimum of 180 hours on the project for the 10 weeks of summer beginning June 3, with an average of 18 hours per week. Zachary will spend a minimum of 120 hours on the project, with an average of 12 hours per week on the project during each of the ten weeks.

We note that these numbers are given as a minimum commitment; more time and efforts may be needed in the early, and final stage of this project for experiments and report/paper writing. We will adjust our meeting frequency accordingly, with two meetings per week on average, and also actively exchange ideas via phone, e-mail, and *Google* hangouts whenever new challenges prompt.

VIII. PEER REVIEWED WORK EXPECTED

As I have done in the past, the project will disseminate the results through workshop/conference presentation/proceedings, and journal publications. We expect this project will lead to the submission of at least one joint peer-reviewed conference paper, as well as the possible submission of a peer-reviewed journal paper based on the feedback and enhancement of the former. Subject to the date/deadline of the conference, we may spend extra time (not included in the commitment above) for the manuscript preparation. It is expected that Zachary will present his findings for the ACM/Math Club and/or as a guest speaker for the networking class that I teach. In addition, we will also seek external/internal supports for Zachary to attend networking conferences and present his work.

The following networking conferences are under our consideration for publication, where all the technical papers go through a rigorous peer-review process by at least three domain experts: IEEE Global Communication Conference, IEEE International Communication Conference, IEEE International Computer Communication and Networking Conferences, and IEEE Sarnoff Symposium. Equally, we will seek for publication in the following journals: IEEE/OSA Journal of Optical Communication and Networking, IEEE Communication Letters, IEEE Journal of Lightwave Technology, Computer Networks, Optical Switching and Networking. Feedbacks/interactions from above leading networking conferences/journals will surely increase both the La Salle's reputation and the quality of our work.

It is also worth mentioning past experience of mine in guiding under-/graduate student research. My two advisees (Michael, and Phanvu) that were supported by Summer Research Grant 2014 have jointly presented their research findings at the undergraduate poster day, the Horold Event as well as the 23-th International Wireless and Optical Communications Conference. As a guest speaker, Phanvu presented his findings at the CSIT 422 Information Security class that I taught to share his findings with other students. Phanvu also published two proceeding papers at the First Workshop on Software-Defined Internets of the Future 2014, and the 2015 IEEE International Conference on Computer Communications and Networks. He attended the first conference and presented his work. We have one co-authored journal paper that passed the first round of review and is currently under revision. During my time at Georgia State University, I have experience in guiding undergraduate student research via the NSF REU (Research for Undergraduate) program for two undergraduate students: Wa'el Belkasim('09) and Dirk Carey('11) on pedagogy study at Georgia State University (GSU). The former student has played an important role in helping GSU establish the first networking lab, while the latter has successfully helped my research group compile a new undergraduate course curriculum: *Introduction to Internet*. Likewise, I have guided four master projects and co-authored a paper with one of the four students. Given my past experience and the high competence of Zachary, we are very confident with the outcome of this summer research.

IX. ATTACHMENTS

A. Faculty Resume

Please see attached document.

B. Student Resume

Please see attached document.

C. Department Chair Endorsement

Please see letter sent electronically by Dr. Jonathan Knappenberger.

YANG WANG

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Jenkintown, PA, 19046   wang@lasalle.edu

EDUCATION

- **Ph.D. in Computer Science**   June 2012
  Georgia State University   Atlanta, GA 30303

- **M.S. in Computer Science**   April 2011
  Georgia State University   Atlanta, GA 30303

- **M.E. in Computer Science and Technology**   April 2007
  Beijing University of Posts and Telecommunications   Beijing, China

- **B.E. in Computer Science and Technology**   June 2004
  Anhui Normal University   Wuhu, China

TEACHING EXPERIENCE

Assistant Professor   La Salle University   Aug. 2013 – Current

- **Courses Taught:** Data Communication, Introduction to Computer Science，LAN and Network Administration, Information Security, Object Programming，Data Structures
- **Lab Development:** Purchased devices and setup the student lab with 10+ CISCO Routers, 20+ switches, serving two networking classes
- **Curriculum Development:** Information Security, Java Programming, Cloud Computing
- **Experiment Design:** BGP, ARP, ICMP, STA, RIP, VLAN, ACL, GNS3

Instructor/TA   Georgia State University   Oct.2007 - Aug.2012

- **Courses Taught:** Computers and Applications, Data Structure, and Introduction to Computer Science，Principle of Programming
- **Courses Assisted:** Computer Networks, Computer Organization, and other freshmen/sophomore computer courses
- **Curriculum Development:** Introduction to the Internet, Optical Networking, Algorithm Analysis and Design, Computer Networks
- **Lab Design/Deployment:** GSU Computer Science Dep. Networking Lab (design available at www.cs.gsu.edu/~ywang/lab.jpg)
- **System Administration:** aNet Lab, maintained the compute/ftp servers running on Window Server 2003

INDUSTRIAL EXPERIENCE

Internap Network Services Corporation   Atlanta, GA   Feb. 2012 –Aug. 2013
Senior Cloud/Integration/QA Engineer

- Internap *Platform-as-a-Service* (PaaS) REST API Research/Design/Development in *PHP*
- OpenStack Swift Research and Development, focusing on the proxy-server, memcache module enhancement.
- Designed/Implemented a *Python*-based Performance Framework, used for *CDN* caching, Cloud Storage Performance Evaluation.
- Designed/Implemented a Dynamic Test Generation Engine for the behavior validation of the *GeoDNS* project.
- Research and Deployment of a multi-homing *BGP*-routing testbed, supporting the *Flow Control Platform* Project (upon an automation framework using *Robot*, *Selenium*, *Jenkins*).
- Research and Deployment of *SimNet*, a virtual software-based PNAP lab for generic routing tests, using *GNS3*, *Quagga*.

FutureWei Technologies   Santa Clara, CA   Sep.2011 – Jan.2012
Senior Network Research Engineer (Research and Innovation Center)

- Completed the research on the algorithm design/complexity analysis for the project of *Smart Phone Mobile Navigation System*.
- Led the research project on the protocol design of the Passive Content-Centric Network (CCN), implemented a *C*-based protocol simulator, found deadlock issues in the vanilla *CCN* and proposed resolving solutions.

JAC Software Corporation   Beijing, China   Mar. - July 2007
Development Manager

- Managed a group of five developers.
- Led the system/database design of the Security Monitoring System, using Visual C#/C++, web service, and serial communication.
- Coordinated with clients for the project progress/requirement change, and monitored the member performance.

Mobile JINGWEI Corporation   Beijing, China   Oct.2004 - Dec.2006
Software Engineer Intern

- Implemented the Report Automation Module for the GIS of Beijing City Project, using Visual C++/ VBA.
- Implemented the course registration module for the 211 CAP project of the Ministry of Education of China, using JSP + Oracle database.

RESEARCH INTERESTS

Teaching-related: Pedagogy in Computer Science Education, Lab/Experiment Design/Implementation, Psychology, Course Curriculum Development

Networking-related: Network Modeling/Analysis/Optimization, Algorithm/Protocol Design in Optical/Wireless Networks, Virtualization, Future Internet, Energy-efficient Networking/Computing, and Cloud Computing

PEER-REVIEWED PUBLICATIONS
Pedagogy
1. **Y. Wang**, T. Blum and M. McCoey, "Teaching a Networking Class for Freshmen: Course Design and Lessons Learned", in Proceedings of the 15th ACM conference on SIG-information technology education (SIGITE), Pages 9-14, 2014
2. X. Cao, **Y. Wang**, A. Caciula, and Yichuan Wang, "*Developing a Multifunctional Network Laboratory for Teaching and Research*", in Proceedings of the 10th ACM conference on SIG-information technology education, Pages 155-160, 2009

Multi-granular Optical Networks
1. **Y. Wang**, X. Cao, A. Caciula, and Q. Hu, "*Batch Scheduling in Optical Networks*", in IEEE/OSA Journal of Optical Communications and Networking, Vol. 5, Issue 2, Pages. 116-126, 2013
2. **Y. Wang,** V. Anand, and X.Cao, "*Waveband Switching: A Scalable and Cost Efficient Solution for the Internet Backbone*", Chapter 10 of book: *Solutions for Sustaining Scalability in Internet Growth,* 2013
3. **Y. Wang**, X. Cao, A. Caciula, and Q. Hu, "*On-line Batch Scheduling in Distributed Optical Networks*", in Proceedings of the IEEE 26th International Parallel and Distributed Processing Symposium Workshops & PhD Forum (IPDPSW), Pages 886-893, 2012
4. **Y. Wang**, X. Cao, "*Batch Scheduling in Optical Burst Networks with Feedback/Feedforward FDLs*", in Proceedings of the IEEE Global Communications Conference (GLOBECOM), Pages 2965-2970, 2012
5. **Y. Wang**, X. Cao, "*Multi-granular Optical Switching: A Classified Overview for the Past and Future*", in IEEE Communications Surveys & Tutorials, Vol.14, Issue 3, Pages 698-713, 2012
6. **Y. Wang**, X. Cao, "*Wavelength Retuning in Multi-granular Optical Networks*", in Proceedings of 20th International Conference on Computer Communications and Networks (ICCCN), Pages 1-6, 2011
7. **Y. Wang**, X. Cao, "*A Study on the Dynamic Waveband Switching in Multi-granular Optical Networks*", in IEEE/OSA Journal of Optical Communications and Networking, Vol.3, No. 5, Pages 390-398, 2011
8. **Y. Wang**, X. Cao, "*Adaptive Waveband Switching in WDM Networks*", in Proceedings of the Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference (OFC/NFOEC), Pages 1-3, 2010
9. **Y. Wang**, X. Cao, "*Distributive Waveband Assignment in Multi-granular Optical*

Networks", in Proceedings of 2010 IEEE International Symposium on Parallel & Distributed Processing (IPDPS), Pages 1-9, 2010

10. **Y. Wang** and X. Cao, "*Non-uniform Waveband Switching in Multi-granular Optical Networks,*" in Proceedings of the IEEE Global Communications Conference (GLOBECOM), Pages 1-6, 2009

11. **Y. Wang** and X. Cao, "*A New Hierarchical Waveband Assignment Algorithm in Multi-granular Optical Networks,*" in Proceedings of 18th International Conference on Computer Communications and Networks (ICCCN), Pages 1-6, 2009

12. X. Cao, Yichuan Wang, **Y. Wang**, and C. Xin, "*Tree-based Burst Aggregation in Optical Burst Switching Networks*", in Proceedings of the ISCA International Conference on Parallel and Distributed Computing (and Communications) Systems (PDCCS), Pages 179-184, 2009

Network Protection

1. Q. Hu, **Y. Wang**, and X. Cao, "*Survivable Network Virtualization for Single Facility Node Failure: a Network Flow Perspective*", in Elsevier Journal of Optical Switching and Networking, Vol. 10, Issue 4, Pages 406-415, 2013

2. **Y. Wang**, X. Cao, "*Multi-granular Waveband Assignment and Protection in WDM Networks*", in IEEE/OSA Journal of Lightwave Technology, Vol.28, Issue 23, Pages 2004-2013, 2010

3. **Y. Wang** and X. Cao, "*Band-segment Protection in Multi-granular Optical Networks,*" in Proceedings of the IEEE Sarnoff Symposium, Pages 1-5, 2009

OFDM-based Optical Networks

1. **Y. Wang**, X. Cao, and C. Qiao, "*Minimize Subcarrier Re-allocation Overhead in SLICE Networks with Dynamic Traffic*", in Proceedings of the Optical Fiber Communication Conference and Exposition and the National Fiber Optic Engineers Conference (OFC/NFOEC), Pages 1-3, 2013

2. S. Shakya, **Y. Wang**, X.Cao, Z. Ye, and C. Qiao, "*Minimize Sub-carrier Reallocation in Elastic Optical Networks using Traffic Prediction*", in Proceedings of the IEEE Global Communications Conference (GLOBECOM), Pages 2374-2379, 2013

3. **Y. Wang**, X. Cao, Q. Hu, and Y. Pan, "*Towards Elastic and Fine-granular Bandwidth Allocation in Spectrum-sliced Optical Networks*", in IEEE/OSA Journal of Optical Communications and Networking, Vol.4, Issue 11, Pages 906-917, 2012

4. **Y. Wang**, X. Cao, and Y. Pan, "*A Study of the Routing and Spectrum Allocation in Spectrum-sliced Elastic Optical Path Networks*", in Proceedings of IEEE International Conference on Computer Communications (INFOCOM), Pages 1503-1511, 2011

5. **Y. Wang**, X. Cao, and Q. Hu, "*Routing and Spectrum Allocation in SLICE Networks*", in Proceedings of the IEEE International Conference on Communications (ICC), Pages 1-5, 2011

Network Virtualization

1. **Y. Wang,** *"Network Virtualization over SLICE Networks"***,** in Proceedings of the 36th IEEE Sarnoff Symposium, Pages 145-149, 2015

4. **Y. Wang**, Q. Hu, and X. Cao, *"A Branch-and-price Framework for Optimal Virtual Network Embedding"*, in Elsevier Journal of Computer Networks, Pages 318-326, 2016

2. **Y. Wang,** P. Chau and Fuyu Chen**,** *"A Framework for Security-Aware Virtual Network Embedding"***,** in Proceedings of IEEE International Conference on Computer Communications and Networks (ICCCN), Pages 1-7, 2015

3. **Y. Wang**, Q. Hu, and X. Cao, *"Connectively As a Service: Towards Optical-based Network Virtualization [Invited]"*, in Proceedings of International Conference on Computing, Networking and Communications, Pages 264-268, 2014

4. Q. Hu**, Y. Wang,** and X. Cao**,** *"Virtual Network Embedding: An Optimal Decomposition Approach"***,** in Proceedings of IEEE International Conference on Computer Communications and Networks (ICCCN), Pages 1-6, 2014

5. Q. Hu**, Y. Wang,** and X. Cao**,** *"Resolve the Virtual Network Embedding Problem: A Column Generation Approach"***,** in Proceedings of IEEE International Conference on Computer Communications (INFOCOM), Pages 410-414, 2013

6. Q. Hu**, Y. Wang,** and X. Cao**,** *"Towards Survivable Network Virtualization"***,** in Proceedings of the IEEE International Conference on Communications (ICC), Pages 2246-2250, 2013

7. Q. Hu**, Y. Wang,** and X. Cao**,** *"Location-constrained Survivable Network Virtualization"***,** in Proceedings of the 35th IEEE Sarnoff Symposium, Pages 1-5, 2012

Content Centric Networks

1. H. Xie, **Y. Wang**, and G. Shi, *"Scale Content Centric Networks via Reactive Routing"*, in Proceedings of the IEEE International Conference on Communications (ICC), Pages 3530-3535, 2013

Wireless Networking

1. X. Cao, B. Chakrabarty, and **Y. Wang**, *"An Energy-efficient Disjoint Path Routing Approach for Wireless Ad-hoc Networks"*, in Proceedings of the ISCA International Conference on Parallel and Distributed Computing (and Communications) Systems (PDCCS), Pages 91-96, 2009

Undergraduate Research

1. P. Chau, and **Y. Wang, "***Security-Awareness in Network Virtualization: A Classified Overview***",** in Proceedings of First Workshop on Software-Defined Internets of the Future, Pages 545-550, 2014,

2. P. Chau, M. Mazzucca and **Y. Wang, "***OVNE: Enabling Network Virtualization over an Optical Substrate***",** in Poster Session of 23th Wireless and Optical Communications Conference, 2014

PROFESSIONAL ACTIVITIES

Oral/Poster Presentations (2009-2015): IEEE MASS, WOCC, IEEE ICC, IEEE ICCCN, IEEE INFOCOM, IEEE IPDPS, IEEE/OSA OFC, IEEE Sarnoff Symposium, ISCA PDCCS, and ACM SIGITE

Reviewer: IEEE Transactions on Computers, IEEE Transactions on Networking, IEEE Transactions on Parallel and Distributed Systems, IEEE Transactions on Cloud Computing, IEEE/OSA Journal of Optical Communications and Networking, IEEE Systems Journal, IEEE Journal on Selected Area in Communication, IEEE Communication Letters, Elsevier Computer Communications, Elsevier Optical Switching and Networking, ETRI Journal, International Journal of Cloud Computing, Springer Photonic Network Communications, Springer Journal of Computer Science and Technology, WOCC'13, IEEE INFOCOM'12,'13, GLOBECOM'10,'12, '14, ICNC'13, '14, '15

Technical Program Committee/Board Member:
- International Conference on Computing, Networking & Communications 2016
- 36th IEEE Sarnoff Symposium 2015
- International Conference on Computing, Networking & Communications 2015
- International Broadband and Photonics Conference, 2015
- International Conference on Computing, Networking & Communications 2014
- International Workshop on Optical Networking (*iWON*) 2013
- Wireless and Optical Communications Conference (*WOCC*) 2013
- Editorial Board, International Journal On Advances in Telecommunications
- Editorial Board, International Journal of Green Computing and Sustainability and Journal of Computer Games and Communication
- Session Chair: IEEE ICCCN 2015

Awarded Grants
- Amazon AWS Education Grant Award ($4000) 2015 – 2016
- IEEE MASS Faculty Travel Grant 2014
- La Salle University Dean's Summer Research Grant 2014: *"Optimal, Efficient, and Secure Network Virtualization: Towards an Agile Future Internet"*
- GSU Ph.D. Dissertation Grant 2012
- IEEE ICCCN Travel Grant 2011
- IEEE INFOCOM Travel Grant 2011
- IEEE IPDPS Travel Grant 2010

NSF-supported Project Experience
- NSF CNS-1117229: *Design and Analysis of Spectrum-sliced Elastic Optical Path Networks* (Drafted the proposal before graduation, and current collaborator)
- NSF CAREER-0813555: *A Design of Multi-granular Switching Framework for Optical Networks* (Research Assistant)

Other Services

- **Chair**, Network and Communication Lab (*http://www.cs.gsu.edu/ncl/*) Research Seminar Series, 2010 - 2011
- **Vice President**, Computer Fan Club, 2003 – 2004
- **Undergraduate Research Advising**: *Wa'el Belkasim('09, NSF REU), Dirk Carey('11, NSF REU), Michael Mazzucca ('13, LSU REU), Phanvu Chau ('13, LSU REU)*

RECENT AWARDS AND HONORS

- *Exemplary Reviewer* for IEEE Communication Letters 2014
- Outstanding Graduate Teaching Award 2012
- Outstanding Graduate Research Award 2010, and 2011
- Best Research Poster Award (*Second Place*) 2010
- Phi Beta Delta Honor Society for International Scholars

Zachary S. McNulty

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EDUCATION

La Salle University, Philadelphia, PA
- Bachelor of Science
    - Majors: Computer Science, Mathematics
- Expected Graduation 2018
- GPA 3.46
- La Salle University Honors Program (January 2015 - Present)

Pocono Mountain West High School, Pocono Summit, PA
- Graduation: June 2014
- GPA: 3.7

COMPUTER SKILLS

- Java Applets and Applications	- Microsoft Encoder	- Windows 7/8	- Adobe Illustrator CS6
- Adobe Photoshop CS6	- JavaScript	- Microsoft Office	

RESEARCH EXPERIENCE

EAAI NSG Challenge: Parameterized Poker Squares (June 2015 –August 2015)
- Completed research with professor in the computer science department to utilize Java to create an algorithm for searching a large solution space for the best results, known as the knapsack problem.
    - Genetic Algorithms
    - Stochastic Ruler.

WORK EXPERIENCE

Jack Frost Big Boulder Ski Resorts, Lake Harmony PA
- Rental Shop Technician (December 2014- Present-Seasonal)
    - Provide excellent customer service by selling and assembling skis and snowboards.
    - Educate customers how to properly pick out and wear equipment.

La Salle University, Philadelphia, PA
- La Salle Recreation Head Score Keeper (August 2014 - Present)
    - Keep time, score and records of intermural flag football games.

Eagle Lake Community Association, Gouldsboro, PA
- Lifeguard (May 2014 – August 2015)
    - Ensure the safety of patrons by enforcing the rules of the facility and responding to emergencies.

LEADERSHIP EXPERIENCE AND ACTIVITIES

La Salle Programming Competition Team (October 2015 – Present)

National Society of Collegiate Scholars (March 2015-Present)

La Salle University Peer Educator (January 2015-present)

Treasurer of the La Salle University Mathematical Association (January 2015 - Present)
- Plan events for the Association to hold as well as manage club communication.

La Salle University Club Ultimate Frisbee (January 2015 - Present)

The Real Freshman of La Salle (August 2015)
- Put on a play for freshman students addressing topics that they will be likely to encounter at college.

Too Many Games Convention Volunteer, Oaks, PA (June 2014-June 2015)
- Large Tournament Manager