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a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU	19b. TELEPHONE NUMBER 305-348-1625

# RPPR Final Report

## as of 11-Aug-2017

Agency Code:

Proposal Number: 62705CSREP  
**INVESTIGATOR(S):**

**Agreement Number: W911NF-13-1-0157**

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Country: USA

DUNS Number: 071298814

EIN: 756000121

**Report Date:** 30-Jul-2017

Date Received: 11-Aug-2017

**Final Report** for Period Beginning 01-May-2013 and Ending 30-Apr-2017

**Title:** Enabling Time-sensitive Applications on Virtualized Computing Systems

**Begin Performance Period:** 01-May-2013

**End Performance Period:** 30-Apr-2017

**Report Term:** 0-Other

Submitted By: Jason Liu

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Phone: (305) 348-1625

**Distribution Statement:** 1-Approved for public release; distribution is unlimited.

**STEM Degrees:** 4

**STEM Participants:** 9

**Major Goals:** System virtualization allows applications to be conveniently deployed with customized execution environments using virtual machines (VMs) and enables them to flexibly share various types of resources with strong isolation among VMs. It is a core technology of public and private cloud computing systems which can elastically provision resources on demand. Many applications can benefit from computing on virtualized systems, including those that have different degrees of timeliness requirements.

The objective of this project is to address the research challenges for delivering strong timeliness guarantees on VMs and efficient timeliness-driven resource management of virtualized systems, thereby supporting applications with different degrees of time constraints to also benefit from virtualization. To achieve the above objective, this project will make research contributions along the following four thrusts:

- 1) Real-time capable VM architecture. This research will produce a new VM scheduling architecture capable of supporting strong timeliness of hosted applications. The contribution will include novel cross-layer scheduling interfaces that allow VM host and guest to cooperatively enforce a virtualized application's timeliness guarantee, and novel enhancements for contemporary VM monitors (VMMs) to improve responsiveness and predictability based on a thorough examination of their timeliness behaviors.
- 2) Timeliness-driven VM resource management. This research will develop novel techniques to efficiently manage a VM's resource allocations based on its timeliness requirement. The contributions will include a new deadline-based resource scheduling hierarchy for supporting applications with stringent time constraints, by addressing their deadlines at guest and host layers holistically, and a new nonlinear-modeling-based resource allocation method for supporting applications with relaxed time constraints by accurately capturing the impact of resource contention and predicting the VMs' resource needs for meeting their desired Quality of Service (QoS).
- 3) Autonomic cloud resource optimization. This research will enable a large virtualized system to automatically optimize its resource allocation to VMs for applications with different time constraints. The contributions include a new timeliness-utility-driven optimization scheme that automatically maximizes the overall timeliness for all virtualized applications, and a new VM-migration-based cross-host optimization technique that accounts for the

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impact of VM migration on application timeliness.

4) Application-driven case studies. This project will provide concrete case studies for the proposed research using important real-world applications, including dynamic data driven robotic control with stringent time constraints, network simulation with relaxed time constraints, and virtual networks of VMs with cross-network timeliness requirements. These applications have distinct timeliness characteristics and are representative of various DOD applications. In addition to these case studies, the investigators will collaborate with DOD researchers to identify and study key applications from their domains.

These four research thrusts are seamlessly connected to ensure the success of the entire project. Thrust I will provide the necessary knobs to control a virtualized application's timeliness behavior, Thrust II will provide the intelligence to tune the knobs according to the application's timeliness requirement, Thrust III will handle the competing needs from different virtualized applications and optimize the entire cloud system's resource management, and finally, Thrust IV will provide a solid platform for validating designs, evaluating prototypes, and getting feedback for further improvements of the previous thrusts.

This project will enable a broad range of time-sensitive applications on virtualized computing systems, thereby generating impact to potentially many DOD areas where the use of virtualization and cloud has value but current technologies do not provide adequate support for time-sensitive workloads. By hosting such applications on customized VMs, it becomes possible for them to be conveniently deployed onto heterogeneous platforms and to efficiently harness available resources. By delivering different degrees of timeliness to different workloads, it becomes possible to support a wide variety of applications.

This project will integrate the research with education at different levels and leveraging the project to broaden participation of students from underrepresented groups. The investigators will collaborate to engage minority students in advanced research and education and provide them with resources available at Florida International University (FIU), University of Florida (UF), and at a national level (e.g., FutureGrid, a multi-university cloud computing testbed). This project's focus on virtualization also provides opportunities for creating unique educational modules and activities. Its research will be integrated in graduate and undergraduate courses offered by the investigators at FIU and UF, and leveraged to develop and disseminate new VM-based course modules.

**Accomplishments:** A PDF document has been submitted.

**Training Opportunities:** 1) The project has supported the training on DOD-related research for four PhD students (Yiqi Xu, Dulcardo Arteaga, Michel Angelo Roger, and Jorge Cabrera), including three Hispanics (Dulcardo Arteaga, Michel Angelo Roger, Jorge Cabrera), at FIU. We have also leveraged funding from other sources to recruit two graduate students at FIU (Kishwar Ahmed and Mohammad Obaida), and one graduate student and two undergraduate students at UF (Kyuho Jeong, Saumitra Aditya and Sebastian Sabogal). These additional students have made significant contributions to the project. The two FIU students were working on HPC modeling and simulation, and the three UF students were working on research and development of virtual networks.

The project has trained the students' research skills in the areas of cloud computing, high-performance computing, distributed systems, storage systems, and virtualization. It has also trained their general skills in technical reading, writing, and presentation. The students supported by this project have made remarkable accomplishments. Yiqi Xu and Dulcardo Arteaga (Hispanic) have successfully defended their PhD thesis and graduated in spring 2016. Yiqi's thesis title is Storage Management of Data-Intensive Computing Systems and Dulcardo's thesis title is Flash Caching for Cloud Computing Systems. Michel Roger (Hispanic), a former FIU master student supported by the project, has joined the FIU PhD program, continuing to make contributions to the project. Many of these students presented their research outcomes at the premier conferences of the field (HPDC, BigData, FAST) and had good opportunities to interact with the researchers and practitioners from the community. Jorge Cabrera performed research on time-sensitive cloud computing. He designed and implemented RTVirt, a new solution to enabling time-sensitive applications (such as emergency planning and management applications) on virtualized systems (such as public and private cloud systems) through cross-layer scheduling.

2) Dr. Figueiredo's lab at UF hosted a female high-school student intern, and an undergraduate student from Brazil in the summer of 2016 who worked on virtual networking software.

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- Results Dissemination:** \* Jason Liu, "Interconnect Model and Integration of MPI Applications", Los Alamos National Laboratory, January 2016.
- \* Jason Liu and Ming Zhao, "Applications of Future Network Technologies to Disaster Management", Workshop on Looking Beyond the Internet: Applications and Services in the Year 2021, January 2016.
- \* Ming Zhao, "Managing I/O Performance of Big Data Systems", Trends in High-Performance Distributed Computing (HPDC), Pittsburgh, PA, March 2016.
- \* Jason Liu, "High-Performance Simulation & Modeling of Computer Systems and Computer Networks At Scale", CENTRA Kickoff Meeting, Taipei, Taiwan, March 2016.
- \* Renato Figueiredo, "IPOP-TinCan Overlay Virtual Network and Applications", Trends in High-Performance Distributed Computing (HPDC), Pittsburgh, PA, March 2016.
- \* Ming Zhao, "It's All About Cache", Invited Talk, New Mexico State University, Las Cruces, NM, April 2016.
- \* Jason Liu, "Scalable Experimentation of SDN Applications", GEFI Workshop, Brussels, Belgium, April 2016.
- \* Jason Liu, "Integrated Modeling for Rapid Assessment and Performance Prediction of HPC Applications", Salishan Conference on High-Speed Computing, Gleneden Beach, Oregon, April 2016.
- \* Kyuho Jeong, "Self-configuring Software-defined Overlay Bypass for Seamless Inter- and Intra-cloud Virtual Networking", 25th International Symposium on High-Performance Parallel and Distributed Computing, May 2016.
- \* Jason Liu, "An Integrated Interconnection Network Model for Large-Scale Performance Prediction", 2016 SIGSIM-PADS Conference, Banff, AB, Canada, May 2016.
- \* Ming Zhao, "It's All about Cache", Invited Talk, Tsinghua University, Beijing, China, June 2016.
- \* Ming Zhao, "It's All about Cache", Invited Talk, Xi'an Dianzi University, Xi'an, Shanxi, China, June 2016.
- \* Ming Zhao, "IBIS: Interposed Big-data I/O Scheduler", Invited Talk, Huazhong University of Science and Technology, Wuhan, Hubei, China, June 2016.
- \* Ming Zhao, "It's All about Cache", Invited Talk, Huazhong University of Science and Technology, Wuhan, Hubei, China, June 2016.
- \* Ming Zhao, "On the Use of Control Theory to Manage Advanced Computer Systems", Invited Talk, University of Science and Technology of China, Hefei, Anhui, China, June 2016.
- \* Ming Zhao, "It's All about Cache", Invited Talk, Shanghai Jiaotong University, Shanghai, China, June 2016.
- \* Ming Zhao, "IBIS: Interposed Big-data I/O Scheduler", 25th International Symposium on High-Performance Parallel and Distributed Computing (HPDC), Kyoto, Japan, June 2016.
- \* Jason Liu, "Toward Integrated Multi-Resolution HPC Modeling for Rapid Performance Prediction", Workshop on Modeling & Simulation of Systems and Applications, Seattle, Washington, August 2016.
- \* Jason Liu, "Modeling and Simulation with Performance & Accuracy Tradeoff", Invited Talk, Arizona State University, Tempe, Arizona, November 2016.
- \* Jason Liu, "Scalable Interconnection Network Models for Rapid Performance Prediction of HPC Applications". 18th International Conference on High Performance Computing and Communications (HPCC), Sydney, Australia, December 2016.
- \* Jason Liu, "Symbiotic Modeling and High-Performance Simulation", Invited Talk, Colorado School of Mines, Golden, Colorado, January 2017.
- \* Jason Liu, "Codesign Performance Prediction for Computational Physics - Interconnect Models", Los Alamos National Laboratory, Los Alamos, New Mexico, January 2017.
- \* Ming Zhao, "It's All about Cache", Invited Talk, University of California, Merced, CA, USA, February 2017.
- \* Ming Zhao, "CacheDedup: In-line Deduplication for Flash Caching", 8th Annual Non-Volatile Memories Workshop (NVMW), San Diego, CA, USA, March, 2017.
- \* Jason Liu, "High-Performance Modeling and Simulation of Computer Networks", Invited Talk, Laboratory of Information, Networking and Communication Sciences (LINCS), Paris, France, April 2017.
- \* Jason Liu, "Distributed Mininet with Symbiosis", IEEE International Conference on Communications (ICC'17), Paris, France, May 2017.
- \* Ming Zhao, "It's All about Cache", Invited Talk, Beihang University, China, USA, June 2017.
- \* Ming Zhao, "It's All about Cache", Invited Talk, Hongkong City University, Hongkong, China, June 2017.
- \* Ming Zhao, "Kaleido: Enabling Efficient Scientific Data Processing on Big-Data Systems", 12th International Conference on Networking, Architecture, and Storage, Shenzhen, Guangdong, China, August 2017.

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**Honors and Awards:** 1) National Science Foundation (NSF) Faculty Early Career Development (CAREER) Award (awarded to Dr. Zhao), "Coordinated QoS-driven Management of Cloud Computing and Storage Resources", 2013 – 2019

The CAREER award is the Foundation's most prestigious award to junior faculty who exemplify the role of teacher-scholars through outstanding research and excellent education. Specifically, Dr. Zhao's CAREER project is creating a coordinated resource management framework that optimizes the allocations of cloud computing and storage resources according to application-desired Quality of Service (QoS). This project's research outcomes will enable virtualized systems to support performance guarantees for modern applications with dynamic and complex behaviors. As a result, a broader range of applications with different QoS requirements will benefit from cloud computing, and cloud services will be able to offer their users more economical QoS-based charging models instead of the currently used resource-capacity-based models. This project's education outcomes will enable systematic education on virtualization and cloud computing from K- 12 to undergraduate and graduate classrooms and prepare a pipeline of students who are equipped with the necessary knowledge and skills in these emerging technologies and prepared to contribute in the coming cloud computing era. ([http://www.nsf.gov/awardsearch/showAward?AWD\\_ID=1253944](http://www.nsf.gov/awardsearch/showAward?AWD_ID=1253944))

2) National Science Foundation Software Infrastructure for Sustainable Innovation (SI2) Award (awarded to Dr. Figueiredo), "SI2-SSE: Peer-to-Peer Overlay Virtual Network for Cloud Computing Research), 2013 – 2016  
The NSF SI2 is a program with the overarching goal of transforming innovations in research and education into sustained software resources that are an integral part of the cyberinfrastructure. Specifically, Dr. Figueiredo's SI2 project addresses the connectivity challenges in cloud computing by developing an open- source scientific software element that allows researchers and users of clouds to seamlessly create virtual networks on demand for distributed virtual machines. To this end, the project creates software-defined virtual networks that support the standard Internet Protocol (IP) and use tunneling of virtual network packets over Peer-to-Peer (P2P) links among virtual machines for scalable and resilient messaging. In addition to the core IP-over-P2P virtual networking, the software provides a framework for configuration, management and monitoring that enables easy deployment of user-defined overlays for inter-cloud research experiments. ([http://www.nsf.gov/awardsearch/showAward?AWD\\_ID=1339737&HistoricalAwards=false](http://www.nsf.gov/awardsearch/showAward?AWD_ID=1339737&HistoricalAwards=false))

3) National Science Foundation Computer Systems Research (CSR) Medium Award (awarded to Drs. Liu and Zhao, PI: Dr. Rangaswami), "NVM-enabled Host-side Caches", 2016 - 2019  
This program is NSF's core area system research. Drs. Liu and Zhao will collaborate, together with other researchers, on memory and storage systems. Non-volatile memory (NVM) is a transformative technology that is dramatically changing how data storage systems of the future are built. This technology allows an unprecedented combination of performance and persistence into a single device. This project will develop a suite of storage caching techniques for this transformative technology along four complementary dimensions. The first two usage dimensions address the selective use of NVM as host-side read caches for persistently stored data as well as using their persistence properties explicitly by developing fault-tolerant write caching solutions. The latter two develop advanced techniques for delivering storage quality of service (QoS) using NVM caches and building caching algorithms that are aware of data reduction techniques, such as deduplication and compression, for the NVM layer. Together, these contributions have the potential to transform enterprise data center storage stacks by readily adopting the best properties of current and future NVM technology. The expected performance benefits apply to a broad spectrum of computer systems and applications. ([https://nsf.gov/awardsearch/showAward?AWD\\_ID=1563883&HistoricalAwards=false](https://nsf.gov/awardsearch/showAward?AWD_ID=1563883&HistoricalAwards=false) and [https://nsf.gov/awardsearch/showAward?AWD\\_ID=1562837&HistoricalAwards=false](https://nsf.gov/awardsearch/showAward?AWD_ID=1562837&HistoricalAwards=false))

4) VMware Graduate Fellowship (awarded to Dr. Zhao's PhD student Yiqi Xu), 2015  
The VMware Graduate Fellowship is a highly competitive fellowship awarded to outstanding graduate students with research aligned with VMware, the leading virtualization company. Each year only a select number of academic departments are invited to nominate up to two of their PhD candidates for consideration and among these candidates only a total of four awards are awarded each year. (<https://labs.vmware.com/academic/vmware-2014-2015-graduate-fellowships>)

5) McKnight Doctoral Fellowship (awarded to Dr. Zhao's PhD student Gregory Jean-Baptise), 2015  
The McKnight Doctoral Fellowship program is designed to address the under-representation of African American and Hispanic faculty at colleges and universities in the state of Florida by increasing the pool of citizens qualified with Ph.D. degrees to teach at the college and university levels. Up to 50 Fellowships are awarded annually to study at one of nine participating Florida universities. Each award provides annual tuition up to \$5,000 (tuition above this amount is waived by the participating institution) for each of three academic years plus an annual stipend of \$12,000. (An additional two years of support at this same level is provided by the participating institution.) (<http://www.fefonline.org/mdf.html>)

**Protocol Activity Status:**

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**Technology Transfer:** Nothing to Report

**PARTICIPANTS:**

**Participant Type:** Faculty

**Participant:** Ming Zhao

**Person Months Worked:**

Project Contribution:

International Collaboration:

International Travel:

National Academy Member:

Other Collaborators:

**Funding Support:**

**Participant Type:** Faculty

**Participant:** Renato Figueiredo

**Person Months Worked:**

Project Contribution:

International Collaboration:

International Travel:

National Academy Member:

Other Collaborators:

**Funding Support:**

**Participant Type:** Graduate Student (research assistant)

**Participant:** Michel Roger

**Person Months Worked:**

Project Contribution:

International Collaboration:

International Travel:

National Academy Member:

Other Collaborators:

**Funding Support:**

**Participant Type:** Faculty

**Participant:** 1) Ming Zhao

**Person Months Worked:**

Project Contribution:

International Collaboration:

International Travel:

National Academy Member:

Other Collaborators:

**Funding Support:**

**Participant Type:** Faculty

**Participant:** 2) Renato Figueiredo

**Person Months Worked:**

Project Contribution:

International Collaboration:

International Travel:

National Academy Member:

Other Collaborators:

**Funding Support:**

**Participant Type:** Graduate Student (research assistant)

**Participant:** Wenji Li

**Person Months Worked:**

Project Contribution:

**Funding Support:**

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International Collaboration:  
International Travel:  
National Academy Member:  
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)

**Participant:** Saman Biok Aghazadeh

**Person Months Worked:**

**Funding Support:**

Project Contribution:  
International Collaboration:  
International Travel:  
National Academy Member:  
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)

**Participant:** Juan Daniel Riveros

**Person Months Worked:**

**Funding Support:**

Project Contribution:  
International Collaboration:  
International Travel:  
National Academy Member:  
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)

**Participant:** Lixi Wang

**Person Months Worked:**

**Funding Support:**

Project Contribution:  
International Collaboration:  
International Travel:  
National Academy Member:  
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)

**Participant:** Gregory Jean-Baptise

**Person Months Worked:**

**Funding Support:**

Project Contribution:  
International Collaboration:  
International Travel:  
National Academy Member:  
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)

**Participant:** Michel Angelo Roger

**Person Months Worked:**

**Funding Support:**

Project Contribution:  
International Collaboration:  
International Travel:  
National Academy Member:  
Other Collaborators:

**Participant Type:** PD/PI

**Participant:** Jason X. Liu

**Person Months Worked:** 1.00

**Funding Support:**

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Project Contribution:  
International Collaboration:  
International Travel:  
National Academy Member: N  
Other Collaborators:

**Participant Type:** Co PD/PI

**Participant:** Renato J. Figueiredo

**Person Months Worked:** 1.00

**Funding Support:**

Project Contribution:  
International Collaboration:  
International Travel:  
National Academy Member: N  
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)

**Participant:** Yiqi Xu

**Person Months Worked:** 9.00

**Funding Support:**

Project Contribution:  
International Collaboration:  
International Travel:  
National Academy Member: N  
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)

**Participant:** Dulcardo Arteaga

**Person Months Worked:** 12.00

**Funding Support:**

Project Contribution:  
International Collaboration:  
International Travel:  
National Academy Member: N  
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)

**Participant:** Jorge Cabrera

**Person Months Worked:** 12.00

**Funding Support:**

Project Contribution:  
International Collaboration:  
International Travel:  
National Academy Member: N  
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)

**Participant:** Michel Angelo Roger

**Person Months Worked:** 12.00

**Funding Support:**

Project Contribution:  
International Collaboration:  
International Travel:  
National Academy Member: N  
Other Collaborators:

**Participant Type:** PD/PI

**Participant:** Jason X. Liu

**RPPR Final Report**  
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**Person Months Worked:** 1.00

**Funding Support:**

Project Contribution:  
International Collaboration:  
International Travel:  
National Academy Member: N  
Other Collaborators:

**Participant Type:** Other (specify)

**Participant:** Ming Zhao

**Person Months Worked:** 3.00

**Funding Support:**

Project Contribution:  
International Collaboration:  
International Travel:  
National Academy Member: N  
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)

**Participant:** Yiqi Xu

**Person Months Worked:** 9.00

**Funding Support:**

Project Contribution:  
International Collaboration:  
International Travel:  
National Academy Member: N  
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)

**Participant:** Dulcardo Arteaga

**Person Months Worked:** 12.00

**Funding Support:**

Project Contribution:  
International Collaboration:  
International Travel:  
National Academy Member: N  
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)

**Participant:** Jorge Cabrera

**Person Months Worked:** 12.00

**Funding Support:**

Project Contribution:  
International Collaboration:  
International Travel:  
National Academy Member: N  
Other Collaborators:

**Participant Type:** Graduate Student (research assistant)

**Participant:** Michel Roger

**Person Months Worked:** 12.00

**Funding Support:**

Project Contribution:  
International Collaboration:  
International Travel:  
National Academy Member: N  
Other Collaborators:

**Participant Type:** Co PD/PI

**RPPR Final Report**  
as of 11-Aug-2017

**Participant:** Renato Figueirato  
**Person Months Worked:** 1.00  
Project Contribution:  
International Collaboration:  
International Travel:  
National Academy Member: N  
Other Collaborators:

**Funding Support:**

**CONFERENCE PAPERS:**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published  
**Conference Name:** 7th IEEE International Conference on Cloud Computing  
Date Received: 31-Aug-2016 Conference Date: 27-Jun-2014 Date Published:  
Conference Location: Anchorage, Alaska  
**Paper Title:** Game Theoretic Modeling of Security and Interdependency in a Public Cloud  
**Authors:** Charles A. Kamhoua, Luke Kwiat, Kevin A. Kwiat, Joon S. Park, Ming Zhao, Manuel Rodriguez  
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published  
**Conference Name:** 12th International Conference on Autonomic Computing  
Date Received: 31-Aug-2016 Conference Date: 07-Jul-2015 Date Published:  
Conference Location: Grenoble, France  
**Paper Title:** QoS-driven Cloud Resource Management through Fuzzy Model Predictive Control  
**Authors:** L. Wang, J. Xu, H. A. Duran-Limon, M. Zhao  
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published  
**Conference Name:** 1st IEEE/IFIP Workshop on Security for Emerging Distributed Network Technologies  
Date Received: 31-Aug-2016 Conference Date: 15-May-2015 Date Published:  
Conference Location: Ottawa, Canada  
**Paper Title:** Multi-level VM Replication based Survivability for Mission-critical Cloud Computing  
**Authors:** Ming Zhao, Francois D'Ugard, Kevin A. Kwiat, Charles A. Kamhoua  
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published  
**Conference Name:** 13th USENIX Conference on File and Storage Technologies  
Date Received: 31-Aug-2016 Conference Date: 16-Feb-2015 Date Published:  
Conference Location: Santa Clara, California  
**Paper Title:** How Much Can Data Compressibility Help to Improve NAND Flash Memory Lifetime?  
**Authors:** Jiangpeng Li, Kai Zhao, Xuebin Zhang, Jun Ma, Ming Zhao, Tong Zhang  
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published  
**Conference Name:** IEEE International Conference on Big Data  
Date Received: 31-Aug-2016 Conference Date: 27-Oct-2014 Date Published:  
Conference Location: Washington, DC  
**Paper Title:** BigCache for Big-data Systems  
**Authors:** Michel Angelo Roger, Yiqi Xu, Ming Zhao  
Acknowledged Federal Support: **Y**

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**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published  
**Conference Name:** Sensor to Cloud Architectures Workshop  
Date Received: 31-Aug-2016 Conference Date: 08-Feb-2015 Date Published:  
Conference Location: Bay Area, California  
**Paper Title:** Seamless Networking Among Edge Devices and Clouds with Fog Social Virtual Networks  
**Authors:** R. Figueiredo, S. Aditya, K. Jeong, K. Subratie  
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published  
**Conference Name:** IEEE International Conference on Cloud Engineering  
Date Received: 31-Aug-2016 Conference Date: 09-Mar-2015 Date Published:  
Conference Location: Tempe, Arizona  
**Paper Title:** Kangaroo: A Tenant-Centric Software-Defined Cloud Infrastructure  
**Authors:** Kaveh Razavi, Ana Ion, Genc Tato, Kyuho Jeong, Renato Figueiredo, Guillaume Pierre, Thilo Kielmann  
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published  
**Conference Name:** IEEE International Conference on Collaborative Computing: Networking, Applications and Worksharing  
Date Received: 31-Aug-2016 Conference Date: 22-Oct-2014 Date Published:  
Conference Location: Miami, Florida  
**Paper Title:** Location-based Timely Cooperation over Social Private Network  
**Authors:** Y. Jung, R. Figueiredo, J. Fortes  
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published  
**Conference Name:** 2015 IEEE International Conference on Big Data (Big Data)  
Date Received: 31-Aug-2016 Conference Date: 29-Oct-2015 Date Published:  
Conference Location: Santa Clara, CA, USA  
**Paper Title:** Enabling scientific data storage and processing on big-data systems  
**Authors:** Saman Biokaghazadeh, Yiqi Xu, Shujia Zhou, Ming Zhao  
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published  
**Conference Name:** 25th ACM International Symposium on High-Performance Parallel and Distributed Computing  
Date Received: 31-Aug-2016 Conference Date: 31-May-2016 Date Published:  
Conference Location: Kyoto, Japan  
**Paper Title:** IBIS: Interposed Big-data I/O Scheduler  
**Authors:** Yiqi Xu, Ming Zhao  
Acknowledged Federal Support: **Y**

**Publication Type:** Conference Paper or Presentation **Publication Status:** 1-Published  
**Conference Name:** 14th USENIX Conference on File and Storage Technologies  
Date Received: 31-Aug-2016 Conference Date: 22-Feb-2016 Date Published: 31-Aug-2016  
Conference Location: Santa Clara, CA  
**Paper Title:** CacheDedup: In-line Deduplication for Flash Caching  
**Authors:** Wenji Li, Gregory Jean-Baptiste, Juan Riveros, Giri Narasimhan, Tony Zhang, Ming Zhao  
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**Conference Name:** 14th USENIX Conference on File and Storage Technologies  
Date Received: 31-Aug-2016 Conference Date: 22-Feb-2016 Date Published: 31-Aug-2016  
Conference Location: Santa Clara, CA  
**Paper Title:** CloudCache: On-demand Flash Cache Management for Cloud Computing  
**Authors:** D. Arteaga, J. Cabrera, J. Xu, S. Sundararaman, M. Zhao  
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**Conference Name:** 25th ACM International Symposium on High-Performance Parallel and Distributed Computing  
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**Paper Title:** Self-configuring Software-defined Overlay Bypass for Seamless Inter- and Intra-cloud Virtual Networking  
**Authors:** Kyuho Jeong, Renato Figueiredo  
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**Conference Name:** 2017 Winter Simulation Conference  
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Conference Location: Las Vegas, NV, USA  
**Paper Title:** Simulation of HPC job scheduling and large-scale parallel workloads  
**Authors:** Mohammad Abu Obaida, Jason Liu  
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**Conference Name:** 10th EAI International Conference on Simulation Tools and Techniques (SIMUTOOLS)  
Date Received: 09-Aug-2017 Conference Date: 11-Sep-2017 Date Published: 11-Sep-2017  
Conference Location: Hong Kong, China  
**Paper Title:** On improving parallel real-time network simulation for hybrid experimentation of software defined networks  
**Authors:** Mohammad Abu Obaida, Jason Liu  
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Date Received: 09-Aug-2017 Conference Date: 20-Sep-2017 Date Published: 20-Sep-2017  
Conference Location: Banff, BC, Canada  
**Paper Title:** An energy efficient demand-response model for high performance computing systems  
**Authors:** Kishwar Ahmed, Jason Liu, Xingfu Wu  
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Conference Location: Paris, France  
**Paper Title:** Distributed mininet with symbiosis  
**Authors:** Rong Rong, Jason Liu  
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Conference Location: Banff, Alberta, Canada  
**Paper Title:** An Integrated Interconnection Network Model for Large-Scale Performance Prediction  
**Authors:** Kishwar Ahmed, Mohammad Obaida, Jason Liu, Stephan Eidenbenz, Nandakishore Santhi, Guillaume ( Acknowledged Federal Support: **Y**

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**Conference Name:** 18th International Conference on High Performance Computing and Communications (HPCC)  
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Conference Location: Sydney, Australia  
**Paper Title:** Scalable interconnection network models for rapid performance prediction of HPC applications  
**Authors:** Kishwar Ahmed, Jason Liu, Stephan Eidenbenz, Joe Zerr  
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**DISSERTATIONS:**

**Publication Type:** Thesis or Dissertation  
**Institution:**  
Date Received: 02-Sep-2015 Completion Date:  
**Title:** is FUZZY MODELING AND CONTROL BASED VIRTUAL MACHINE RESOURCE MANAGEMENT  
**Authors:**  
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**Institution:** Florida International University  
Date Received: 31-Aug-2016 Completion Date: 3/18/16 4:54PM  
**Title:** Storage Management of Data-Intensive Computing Systems  
**Authors:** Yiqi Xu  
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**Institution:** Florida International University  
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**Title:** Flash Caching for Cloud Computing Systems  
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# Accomplishments

## 1. Foreword

System virtualization allows applications to be conveniently deployed with customized execution environments using VMs and enables them to flexibly share various types of resources with strong isolation among VMs. It is a core technology of public and private cloud computing systems which can elastically provision resources on demand. Many applications can benefit from computing on virtualized systems, including those that have different degrees of timeliness requirements. For example, for a brain-machine interface (BMI) system that consists of signal recording, brain modeling, and robotic control subject to stringent time constraint for each closed-loop, virtualization allows the model computation to transparently and efficiently share resources with best-effort tasks (including offline computation) using isolated VMs; For a big-data system that needs responsive data processing for the purpose of visualization or decision-making, virtualized cloud systems can provide on-demand, large-scale computing without requiring a dedicated large infrastructure; For a distributed simulation/emulation experiment that requires real-time interactions with real-world applications, large numbers of VMs can be used to model a ultra-scale networked system and study its important properties such as security and resilience.

It is challenging for virtualized systems to deliver the desired timeliness to hosted applications, because of the following important reasons.

- 1) Typical VMs are designed for general-purpose usage and are not tailored for responsive and predictable computing; applications may not achieve their desired timeliness guarantees when hosted on a VM because precise timing within a guest is not enforced by a general-purpose VMM.
- 2) The high resource consolidation enabled by virtualization (and multi-core hardware) also creates *complex* and *dynamic* resource contention and performance interference. Such time-sensitive applications are particularly vulnerable to variations of resource availability, which makes it especially difficult to meet and sustain their QoS on virtualized systems.
- 3) The resource management on a virtualized system is typically optimized for fair sharing and for maximizing overall throughput, but not for timeliness QoS. Consequently, when the resources are shared by multiple VMs hosting applications with different time constraints, the system cannot allocate the necessary resources in time to meet their timeliness requirements.

The objective of this project is to address the research challenges for delivering strong timeliness guarantees on virtual machines (VM) and efficient timeliness-driven resource management of virtualized systems, thereby supporting applications with different degrees of time constraints to also benefit from virtualization.

## 2. Statement of Problems Studied

To achieve the above objective, this project will make research contributions along the following four thrusts:

- 1) *Real-time capable VM architecture.* This research will produce a new VM scheduling architecture capable of supporting strong timeliness of hosted applications. The contribution will include novel cross-layer scheduling interfaces that allow VM host and guest to cooperatively enforce a virtualized application's timeliness guarantee, and novel enhancements for contemporary VM monitors (VMMs) to improve responsiveness and predictability based on a thorough examination of their timeliness behaviors.
- 2) *Timeliness-driven VM resource management.* This research will develop novel techniques to efficiently manage a VM's resource allocations based on its timeliness requirement. The contributions will include a new deadline-based resource scheduling hierarchy for supporting applications with stringent time constraints, by addressing their deadlines at guest and host layers holistically, and a new nonlinear-modeling-based resource allocation method for supporting applications with relaxed time constraints by accurately capturing the impact of resource contention and predicting the VMs' resource needs for meeting their desired Quality of Service (QoS).
- 3) *Autonomic cloud resource optimization.* This research will enable a large virtualized system to automatically optimize its resource allocation to VMs for applications with different time constraints. The contributions include a new timeliness-utility-driven optimization scheme that automatically maximizes the overall timeliness for all virtualized applications, and a new VM-migration-based cross-host optimization technique that accounts for the impact of VM migration on application timeliness.
- 4) *Application-driven case studies.* This project will provide concrete case studies for the proposed research using important real-world applications, including dynamic data driven robotic control with stringent time constraints, network simulation with relaxed time constraints, and virtual networks of VMs with cross-network timeliness requirements. These applications have distinct timeliness characteristics and are representative of various DOD applications. In addition to these case studies, the investigators will collaborate with DOD researchers to identify and study key applications from their domains.

These four research thrusts are seamlessly connected to ensure the success of the entire project. Thrust I will provide the necessary knobs to control a virtualized application's timeliness behavior, Thrust II will provide the intelligence to tune the knobs according to the application's timeliness requirement, Thrust III will handle the competing needs from different virtualized applications and optimize the entire cloud system's resource management, and finally, Thrust IV will provide a solid platform for validating designs, evaluating prototypes, and getting feedback for further improvements of the previous thrusts.

This project will enable a broad range of time-sensitive applications on virtualized computing systems, thereby generating impact to potentially many DOD areas where the use of virtualization and cloud has value but current technologies do not provide adequate support for time-sensitive workloads. By hosting such applications on customized VMs, it becomes possible for them to be conveniently deployed onto heterogeneous platforms and to efficiently harness available resources. By delivering different degrees of timeliness to different workloads, it becomes possible to support a wide variety of applications.

This project will integrate the research with education at different levels and leveraging the project to broaden participation of students from underrepresented groups. The investigators will collaborate to

engage minority students in advanced research and education and provide them with resources available at Florida International University (FIU), University of Florida (UF), and at a national level (e.g., FutureGrid, a multi-university cloud computing testbed). This project's focus on virtualization also provides opportunities for creating unique educational modules and activities. Its research will be integrated in graduate and undergraduate courses offered by the investigators at FIU and UF, and leveraged to develop and disseminate new VM-based course modules.

The project lasted for three years plus another eight months with no-cost extension. We have completed our development efforts on all the aforementioned Thrusts. Below, we summarize the specific tasks we have accomplished.

### 3. Summary of the Most Important Results

#### 3.1 Research Accomplishments

- 1) Research and development of RTVirt to support real-time computing on virtualized systems through cross-layer scheduling. First, it provides a new virtualization architecture that enables cross-layer communication and coordination between the host-level VM scheduler and guest-level application schedulers and supports the diverse timeliness requirements of virtualized applications. This cross-layer interface is built upon paravirtualization (specifically hypercalls and shared memory) and supports low-latency and low-overhead interactions between the two levels of schedulers for co-scheduling time-sensitive applications. Second, based on this cross-layer scheduling architecture, RTVirt enables work-conserving, multiprocessor schedulers with strong timeliness guarantees and efficient CPU bandwidth utilization. It supports both uniprocessor and multiprocessor VMs hosting various number of real-time applications (RTAs) and non-RTAs with dynamic arrivals and dynamically changing parameters. RTVirt is prototyped on a widely used virtualization framework (Xen) and evaluated using a variety of benchmarks. The results show that it can meet application deadlines in complex and dynamic settings, and substantially outperform the existing solutions in terms of both timeliness and resource utilization. Experiment results from RTVirt show that: 1) it meets stringent timeliness requirements (meeting at least 99% of all the deadlines or a 99.9<sup>th</sup> percentile tail-latency target) for virtualized applications in complex and dynamic settings. At the same time, it makes efficient use of the resources, and saves up to 50.2% of CPU bandwidth compared to the state-of-the-art works; 2) RTVirt also supports VMs with dynamic bandwidth requirements hosting dynamic RTAs, which cannot be handled by existing solutions; 3) RTVirt allows real-world applications such as video streaming servers to deliver guaranteed streaming rates and memcached services to substantially cut down their tail latencies, when they are run on VMs and under intensive resource contention; 4) Lastly, the results show that RTVirt has good scalability and low overhead (less than 1%) when running 100 virtualized RTAs concurrently on the same host. We are currently preparing to submit these results in paper at a top conference.
- 2) We have created a cross-layer VM resource management approach which allows coarse-grained, low-overhead cooperation between VM host and guest layers in order to improve application performance and meet its QoS target. Specifically, this approach supports two types of such cross-layer optimization. First, guest-to-host optimization exploits guest-layer application knowledge to capture dynamic workload characteristics and improve the modeling of VM resource usage. Second, host-to-guest optimization enables the host-layer scheduler to feedback resource allocation decision and adapt guest-layer application configuration. These two aspects of cross-layer optimization are

integrated into a fuzzy-modeling-based resource management system which uses fuzzy logic to model VM resource demand online and allocate resource dynamically according to application QoS requirement. This approach is incorporated in a two-level cloud resource management framework where at the VM host level the node controllers optimizes dynamic VM resource allocations within individual hosts, and at the cloud zone level the global scheduler coordinates the node controllers to optimize resource utilization across hosts through dynamic VM migrations. The results show that the framework can provide excellent QoS guarantees to VMs running dynamic workloads and can optimize the performance for more than 100 concurrent VMs across multiple hosts. These results were published and presented at ICAC'15.

- 3) Research and development of CloudCache, an on-demand cache management solution that can make effective use of solid-state caches to meet the VMs' performance requirements and reduce the caching device wear-out. First, to support on-demand cache allocation, CloudCache considers a new cache demand model, Reuse Working Set (RWS), to capture only the data with good temporal locality, and uses the Reuse Working Set Size (RWSS) to capture a workload's cache demand. It then uses prediction methods to estimate a workload's cache demand online, and new admission policies to admit only the RWS into the cache, thereby maximizing the workload's performance while minimizing the wear-out of the caching device. Second, to handle situations where a cache is insufficient to meet all the VMs' demands, CloudCache employs a dynamic cache migration approach to balance cache load across hosts by live migrating cached data along with the VMs. It includes both on-demand migration of dirty data and background migration of RWS to minimize the impact to a migrating VM. It also supports rate limiting on the data transfer to minimize the impact to other co-hosted VMs. The results from CloudCache show that: 1) it can be seamlessly deployed onto existing cloud systems as a drop-in solution and transparently provide caching and on-demand cache management; 2) RWSS-based cache allocation can substantially reduce cache usage and wear-out at the cost of only small performance loss in the worst case. Compared to the WSS-based cache allocation, the RWSS-based method reduces a workload's cache usage by up to 76%, lowers the amount of writes sent to cache device by up to 37%, while delivering the same I/O latency performance. Compared to the case where the VM can use the entire cache, the RWSS-based method saves even more cache usage while delivering an I/O latency that is only 1% slower at most; 3) the dynamic cache migration approach reduces the VM's I/O latency by 93% compared to no cache migration, and causes at most 21% slowdown to the co-hosted VMs during the migration; and 4) combining these two techniques, CloudCache is able to improve the average hit ratio of 12 concurrent VMs by 28% and reduce their average 90th percentile I/O latency by 27%, compared to the case without cache allocation. These results of this study were published and presented at FAST'16.
- 4) Research and development of CacheDedup, a solution that addresses the capacity and endurance limitations of solid-state caching using inline deduplication. First, it is based on a novel architecture that integrates the caching of data and metadata (source addresses and fingerprints of the data) and efficiently manages these two components. Second, it includes duplication-aware cache replacement algorithms (D-LRU, D-ARC) that can exploit the knowledge of data duplication to improve flash cache performance and endurance. The study of CacheDedup also includes a rigorous analysis of the algorithms which proves that they do not waste valuable cache space and that they are competitive when compared with the optimal algorithm. The results from CacheDedup show

that: 1) it substantially outperforms the traditional cache replacement algorithms (LRU and ARC) by reducing the cache miss ratio by up to 20%, I/O latency by 51%, and the writes sent to flash memories by 89%; 2) it can effectively deduplicate data both within a workload and across multiple workloads that share the cache by lowering the miss ratio by 11% and the I/O latency by 12% while reducing the writes sent to the cache device by 81%; 3) the theoretical analysis of the algorithms proves that they do not waste valuable cache space and that they are competitive when compared with the optimal algorithm; 4) this approach can be extended to also support both compression and deduplication and improve the read hit ratio by 12.56% compared to the related work; and 5) its throughput overhead is negligible and the latency overhead from fingerprinting can be overlapped with concurrent I/O operations and compensated by the hit ratio gain from deduplication. In terms of space overhead, CacheDedup needs <4% of the cache space to store the deduplication metadata in order for the algorithms to achieve peak performance. These results of this study were published and presented at FAST'16.

- 5) Research and development of IBIS, an Interposed Big-data I/O Scheduler, to provide I/O performance differentiation for competing applications in a shared big-data cloud system. It transparently intercepts, isolates, and schedules an application's different phases of I/Os via an I/O interposition layer on every data node in a big-data system. It provides a new, adaptive proportional-share I/O scheduler, SFQ(D2), to allow applications to share the I/O service of each data node with good fairness and resource utilization. Finally, it enables the distributed I/O schedulers to coordinate with one another and achieve proportional sharing of the big-data system's total I/O service in a scalable manner. The results from the IBIS show that: 1) it is able to support the I/O management of diverse applications from different big-data frameworks including Hadoop and Hive; 2) it can effectively achieve total-service proportional bandwidth sharing for diverse applications in the system, and support various important performance policies; 3) it achieves strong performance isolation for a less I/O-intensive workload (WordCount, Facebook2009, TPC-H) when under heavy contention from a highly I/O-intensive application (TeraGen and TeraSort), which outperforms native Hadoop by 99% for WordCount and 15% for TPC-H queries. This result is accomplished while still allowing the competing application to make good progress and to fully utilize the storage bandwidth (<4% reduction in total throughput); 4) it can also achieve excellent proportional slowdown for competing applications (TeraSort vs. TeraGen) and outperforms native Hadoop by 30%; and 5) finally, the use of IBIS introduces small overhead in terms of both application runtime (<4% slowdown) and resource usages. The results of this study were published and presented at HPDC'15.
- 6) Research and development of Kaleido, a solution that addresses the lack of support of scientific data formats in existing big-data systems by enabling widely used big-data frameworks to directly store and process data stored in self-describing formats commonly used by the scientific community. Specifically, it enables Hadoop to efficiently store NetCDF data on HDFS and process them in MapReduce using convenient APIs. It also enables Hive to support standard queries on NetCDF data, transparently to users. The results from the Kaleidos show that: 1) it allows self-describing data (NetCDF3) to be directly stored on a big-data file system (HDFS) and be directly used by big-data jobs (MapReduce) and queries (Hive); and 2) it achieves substantial speedup (up to 20 times) and space saving (83% reduction), compared to the traditional approach which has to convert NetCDF data to CSV format for Hadoop and Hive to use them. The results of this study were published and

presented at the Big Data in the Geosciences Workshop (co-held with 2015 IEEE International Big Data Conference).

- 7) We have developed improved network virtualization software that allows the deployment of easy-to-manage, user-level virtual private network (VPN) overlays. Among key features of the improved open-source IP-over-P2P (IPOP – <http://www.ipop-project.org>), the software creates end-to-end virtual private network tunnels among devices connected to a trusted online social network service through the standard XMPP protocol, uses the standard STUN/TURN protocols for NAT traversal, supports virtual private addresses for both IPv4 and IPv6 protocols, and supports transparent VM migration without interrupting VM communications (a feature key to the moving-target defense approach), and a layer-2 “switch mode” of operation that allows the virtual network software to bind to a software bridge and handle Ethernet messages. The software runs on commodity desktop/servers (Linux, Windows), as well as mobile and embedded devices (Android, OpenWRT wireless routers, and Raspberry Pi). An article on the IPOP-TinCan architecture was published in the ICST Transactions on Collaborative Computing, and papers on the use of IPOP in edge/cloud and collaborative computing were published in the SCAW workshop, CollaborateCom, and IEEE International Conference on Cloud Engineering (IC2E).
- 8) Research and development of VIAS, (VirtuAlization Acceleration over SDN) – that delivers the flexibility of overlays for inter-cloud virtual private networking, while transparently applying SDN techniques (available in existing OpenFlow hardware or software switches) to selectively bypass overlay tunneling and achieve near-native performance for TCP/UDP flows within a provider. Architecturally, VIAS is unique in how it integrates SDN and overlay controllers in a distributed fashion to coordinate the management of virtual network links and flows. The approach is self-organizing, whereby overlay nodes can detect that peer endpoints are in the same network and program bypass flows between OpenFlow switches. While generally applicable, VIAS in particular applies to nested VMs/containers across cloud providers, supporting seamless communication within and across providers. VIAS has been implemented as an extension to an existing virtual network overlay platform (IP-overP2P, IPOP) by integrating OpenFlow controller functionality with distributed overlay controllers. We have also studied effective SDN modeling and simulation techniques, by using a novel method called simulation symbiosis, where we apply an abstract network model to coordinate the distributed emulation instances, that are superimposed to represent the target SDN network. We used this method to extend Mininet for distributed emulation. Mininet is a container-based emulation environment for studying networks with virtual hosts and OpenFlow-enabled virtual switches on Linux. We also applied real-time network simulation to enable simulation to operate in real time and allow experiments with simulated, emulated, and real network components acting in concert to test SDN network applications or protocols. Results from VIAS have been published at the HPDC’16. The symbiosis approach has been published in ICC’16. The real-time simulation study has been accepted for publication at SIMUTOOLS’17.
- 9) Our research and development efforts also expanded to study HPC systems. We focus on two aspects in this direction. One aspect of research is to model and simulate HPC architectures and scientific applications. In collaboration with researchers at the Los Alamos National Laboratory, we developed a simulator called Performance Prediction Toolkit (PPT). In particular, we studied interconnection network models. Another aspect of research is to study HPC job scheduling for

performance and power management. We developed an HPC job scheduling simulator, and use it to study energy-efficient demand-response models for HPC job scheduling. Our work in this topic has been published at SIGSIM-PADS'16 and HPCC'16 and will appear at MASCOTS'17 and WSC'17.

### 3.2 Education Accomplishments

- 1) The project has supported the training on DOD-related research for four PhD students (Yiqi Xu, Dulcardo Arteaga, Michel Angelo Roger, and Jorge Cabrera), including three Hispanics (Dulcardo Arteaga, Michel Angelo Roger, Jorge Cabrera), at FIU. We have also leveraged funding from other sources to recruit two graduate students at FIU (Kishwar Ahmed and Mohammad Obaida), and one graduate student and two undergraduate students at UF (Kyuho Jeong, Saumitra Aditya and Sebastian Sabogal). These additional students have made significant contributions to the project. The two FIU students were working on HPC modeling and simulation, and the three UF students were working on research and development of virtual networks.

The project has trained the students' research skills in the areas of cloud computing, high-performance computing, distributed systems, storage systems, and virtualization. It has also trained their general skills in technical reading, writing, and presentation. The students supported by this project have made remarkable accomplishments. Yiqi Xu and Dulcardo Arteaga (Hispanic) have successfully defended their PhD thesis and graduated in spring 2016. Yiqi's thesis title is Storage Management of Data-Intensive Computing Systems and Dulcardo's thesis title is Flash Caching for Cloud Computing Systems. Michel Roger (Hispanic), a former FIU master student supported by the project, has joined the FIU PhD program, continuing to make contributions to the project. Many of these students presented their research outcomes at the premier conferences of the field (HPDC, BigData, FAST) and had good opportunities to interact with the researchers and practitioners from the community. Jorge Cabrera performed research on time-sensitive cloud computing. He designed and implemented RTVirt, a new solution to enabling time-sensitive applications (such as emergency planning and management applications) on virtualized systems (such as public and private cloud systems) through cross-layer scheduling.

- 2) Dr. Figueiredo's lab at UF hosted a female high-school student intern, and an undergraduate student from Brazil in the summer of 2016 who worked on virtual networking software.