High Performance Migration Framework for MPI Applications on HPC Cloud

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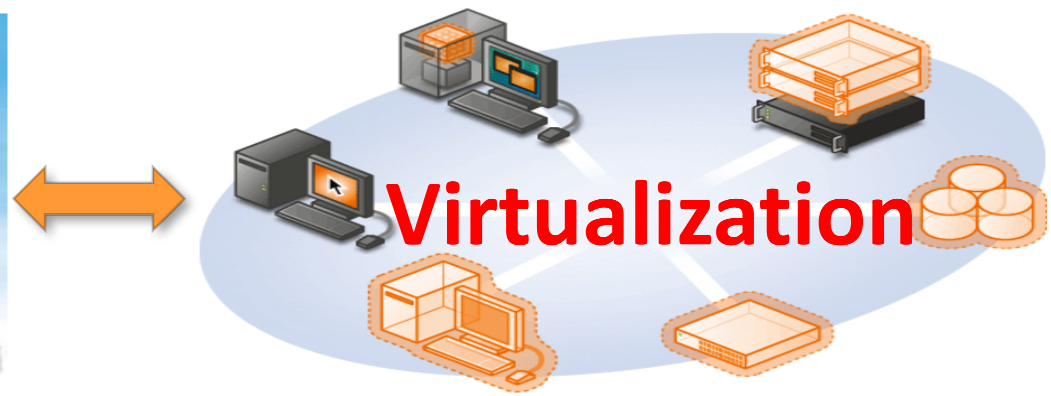
Outline

- Introduction
- Problem Statement
- Design
- Performance Evaluation
- Conclusion & Future Work

Cloud Computing and Virtualization

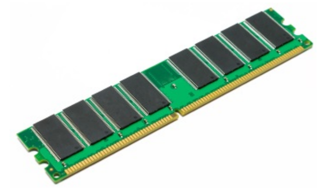


- Cloud Computing focuses on maximizing the effectiveness of the shared resources
- Virtualization is the key technology for resource sharing in the Cloud
- Widely adopted in industry computing environment
- IDC Forecasts Worldwide Public IT Cloud Services spending will reach $195 billion by 2020 (Courtesy: http://www.idc.com/getdoc.jsp?containerId=prUS41669516)

Drivers of Modern HPC Cluster and Cloud Architecture

Multi-/Many-core Processors

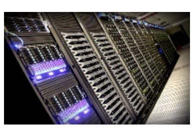
Accelerators (GPUs/Co-processors)



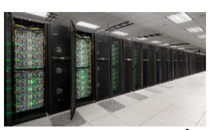
Large memory nodes (Upto 2 TB)

High Performance Interconnects – InfiniBand (with SR-IOV) <1usec latency, 200Gbps Bandwidth>

- Multi-core/Many-core technologies
- Accelerators (GPUs/Co-processors)
- Large memory nodes
- Remote Direct Memory Access (RDMA)-enabled networking (InfiniBand and RoCE)
- Single Root I/O Virtualization (SR-IOV)



SDSC Comet

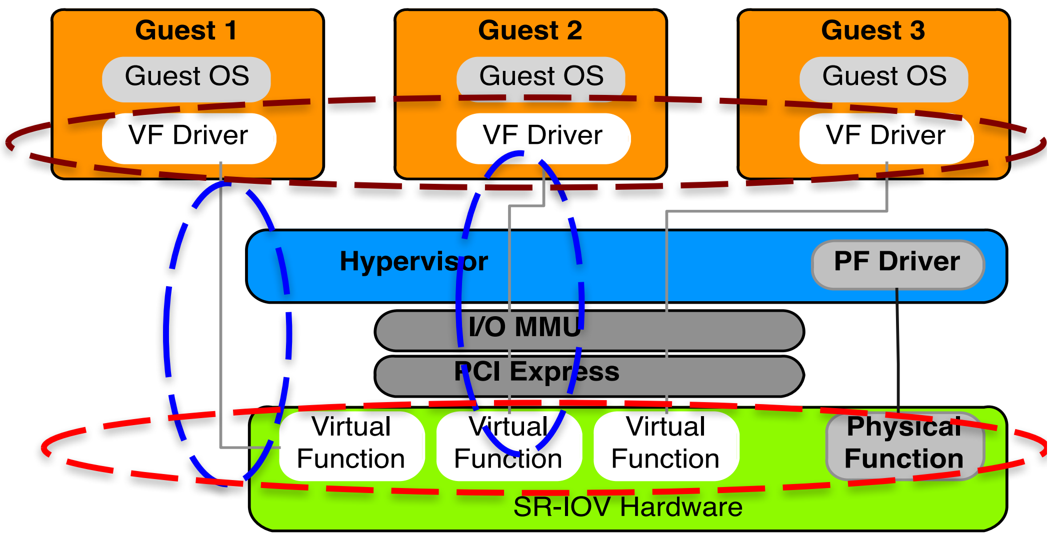


TACC Stampede

Microsoft Azure
amazon web services EC2
ORACLE Cloud
Chameleon Cloud

Single Root I/O Virtualization (SR-IOV)

- SR-IOV is providing new opportunities to design HPC cloud with very little low overhead
- Allows a single physical device, or a Physical Function (PF), to present itself as multiple virtual devices, or Virtual Functions (VFs)
- VFs are designed based on the existing non-virtualized PFs, no need for driver change
- Each VF can be dedicated to a single VM through PCI pass-through



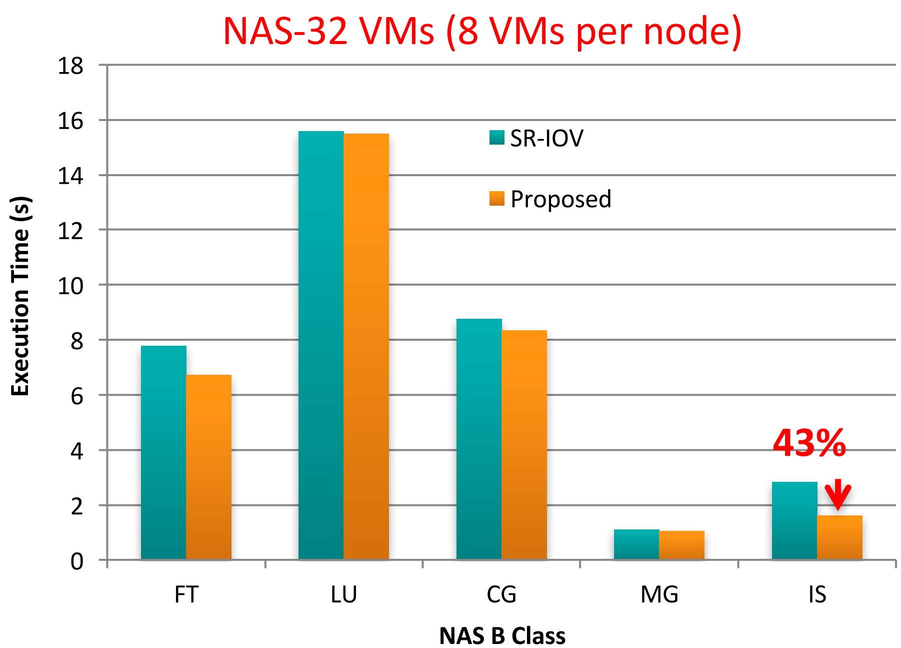
Building HPC Cloud with SR-IOV and InfiniBand

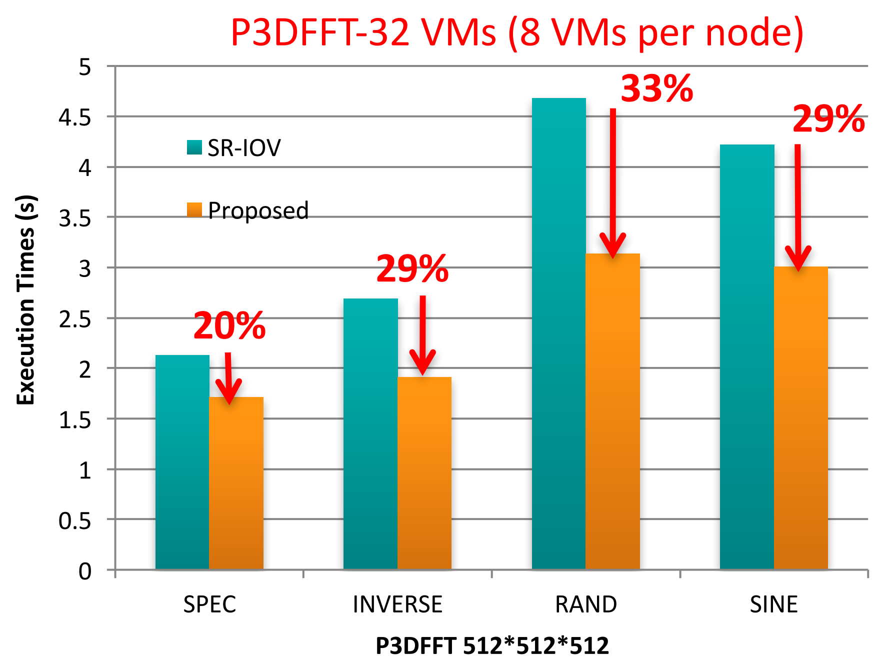
- High-Performance Computing (HPC) has adopted advanced interconnects and protocols
  - InfiniBand
  - 10/40/100 Gigabit Ethernet/iWARP
  - RDMA over Converged Enhanced Ethernet (RoCE)
- Very Good Performance
  - Low latency (few micro seconds)
  - High Bandwidth (200 Gb/s with HDR InfiniBand)
  - Low CPU overhead (5-10%)
- OpenFabrics software stack with IB, iWARP and RoCE interfaces are driving HPC systems

Overview of the MVAPICH2 Project

- High Performance open-source MPI Library for InfiniBand, Omni-Path, Ethernet/iWARP, and RDMA over Converged Ethernet (RoCE)
  - MVAPICH (MPI-1), MVAPICH2 (MPI-2.2 and MPI-3.0), Started in 2001, First version available in 2002
  - MVAPICH2-X (MPI + PGAS), Available since 2011
  - Support for GPGPUs (MVAPICH2-GDR) and MIC (MVAPICH2-MIC), Available since 2014
  - **Support for Virtualization (MVAPICH2-Virt support VM, Docker, Singularity, etc.), Available since 2015**
  - Support for Energy-Awareness (MVAPICH2-EA), Available since 2015
  - Support for InfiniBand Network Analysis and Monitoring (OSU INAM) since 2015
  - **Used by more than 2,825 organizations in 85 countries**
  - **More than 432,000 (> 0.4 million) downloads from the OSU site directly**
  - Empowering many TOP500 clusters (June '17 ranking)
    - **1st ranked 10,649,640-core cluster (Sunway TaihuLight) at NSC, Wuxi, China**
    - 15th ranked 241,108-core cluster (Pleiades) at NASA
    - 20th ranked 522,080-core cluster (Stampede) at TACC
    - 44th ranked 74,520-core cluster (Tsubame 2.5) at Tokyo Institute of Technology and many others
  - Available with software stacks of many vendors and Linux Distros (RedHat and SuSE)
  - **http://mvapich.cse.ohio-state.edu**
- Empowering Top500 systems for over a decade
  - System-X from Virginia Tech (3rd in Nov 2003, 2,200 processors, 12.25 TFlops)
  - Sunway TaihuLight (1st in Jun'17, 10M cores, 100 PFlops)

Application Performance on VM with MVAPICH2

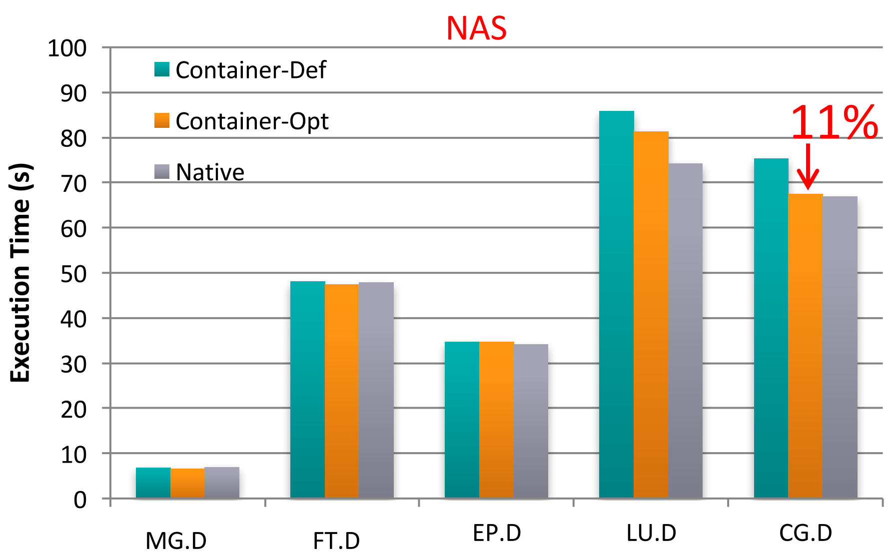


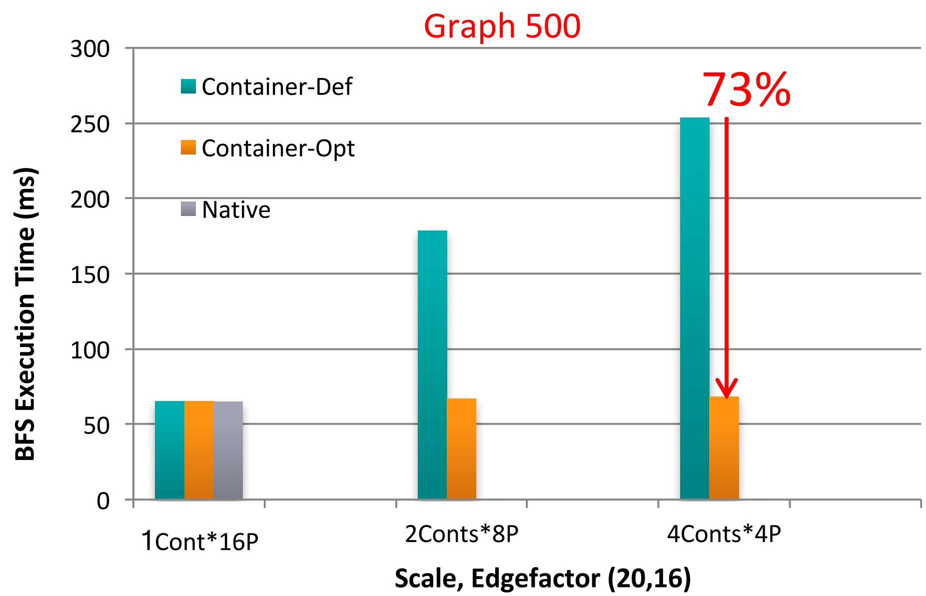


- Proposed design delivers up to 43% (IS) improvement for NAS
- Proposed design brings 29%, 33%, 29% and 20% improvement for INVERSE, RAND, SINE and SPEC

J. Zhang, X. Lu, J. Jose and D. K. Panda, *High Performance MPI Library over SR-IOV Enabled InfiniBand Clusters*, HiPC, 2014

Application Performance on Docker with MVAPICH2

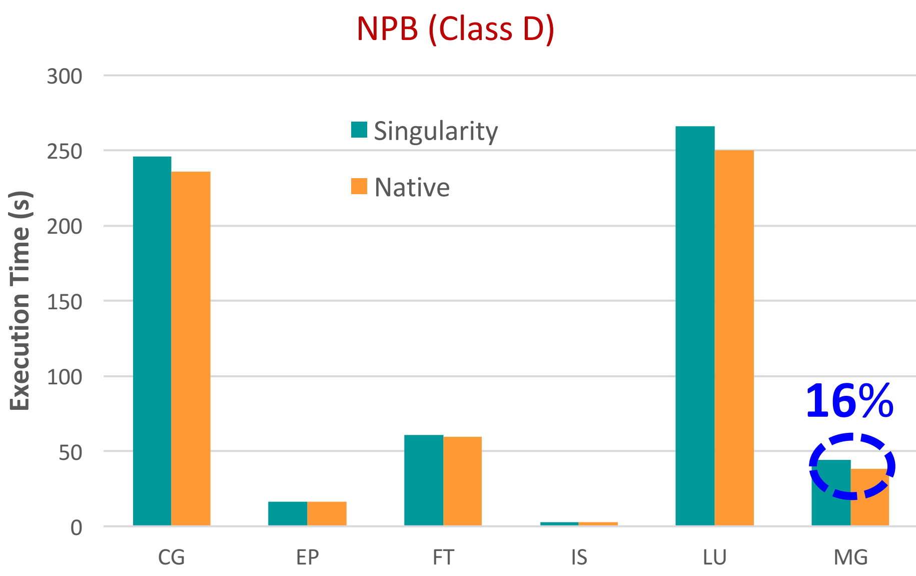


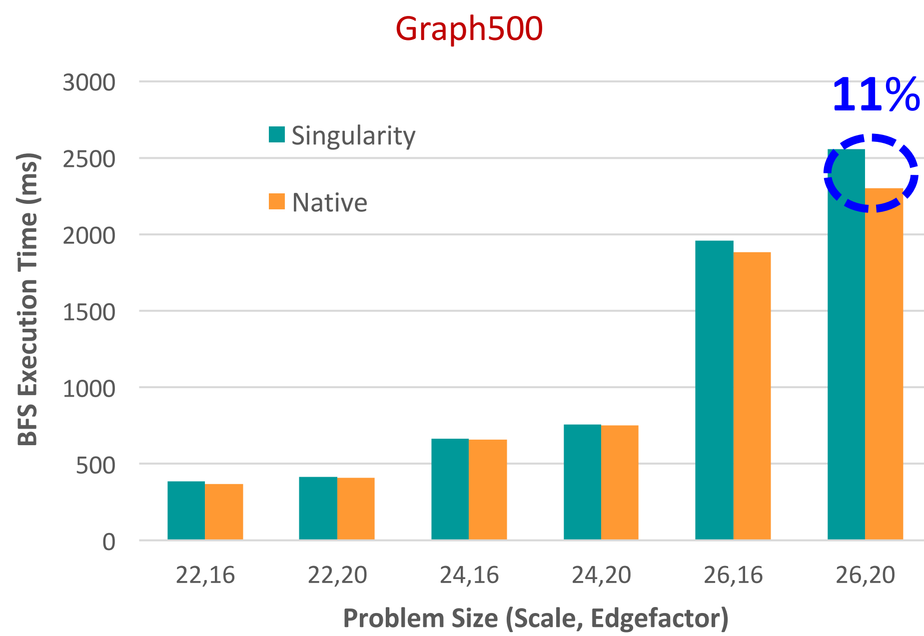


- 64 Containers across 16 nodes, pining 4 Cores per Container
- Compared to Container-Def, up to 11% and 73% of execution time reduction for NAS and Graph 500
- Compared to Native, less than 9 % and 5% overhead for NAS and Graph 500

J. Zhang, X. Lu, D. K. Panda. High Performance MPI Library for Container-based HPC Cloud on InfiniBand, ICPP, 2016

Application Performance on Singularity with MVAPICH2

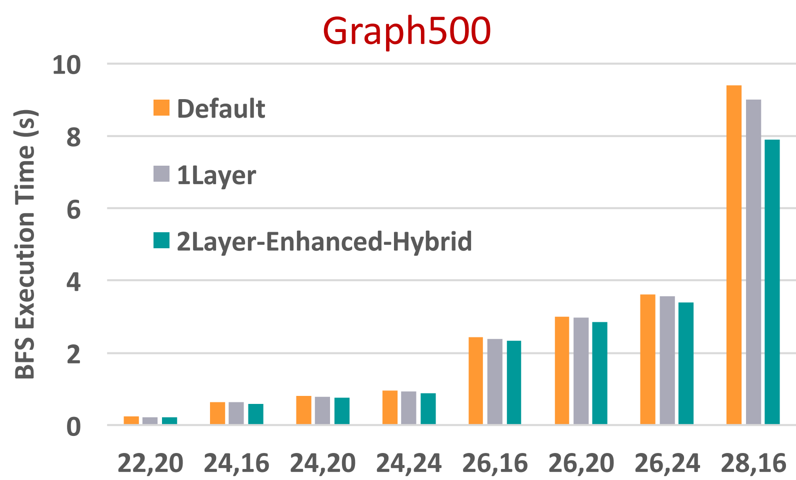


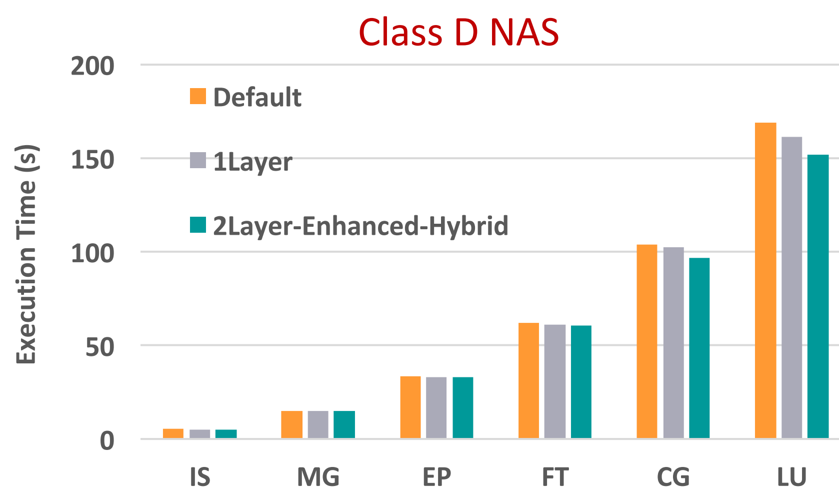


- 512 Processes across 32 nodes
- Less than 16% and 11% overhead for NPB and Graph500, respectively

J. Zhang, X. Lu, D. K. Panda. Is Singularity-based Container Technology Ready for Running MPI Applications on HPC Clouds? UCC, 2017

Application Performance on Nested Virtualization Env. with MVAPICH2





- 256 processes across 64 containers on 16 nodes
- Compared with Default, enhanced-hybrid design reduces up to 16% (28,16) and 10% (LU) of execution time for Graph 500 and NAS, respectively
- Compared with 1Layer case, enhanced-hybrid design also brings up to 12% (28,16) and 6% (LU) benefit.

J. Zhang, X. Lu and D. K. Panda, *Designing Locality and NUMA Aware MPI Runtime for Nested Virtualization based HPC Cloud with SR-IOV Enabled InfiniBand*, VEE, 2017

Execute Live Migration with SR-IOV Device

```
[root@sandy1:migration]$
[root@sandy1:migration]$ssh sandy3-vm1 lspci
root@sandy3-vm1's password:
00:00.0 Host bridge: Intel Corporation 440FX - 82441FX PMC [Natoma] (rev 02)
00:01.0 ISA bridge: Intel Corporation 82371SB PIIX3 ISA [Natoma/Triton II]
00:01.1 IDE interface: Intel Corporation 82371SB PIIX3 IDE [Natoma/Triton II]
00:01.2 USB controller: Intel Corporation 82371SB PIIX3 USB [Natoma/Triton II] (rev 01)
00:01.3 Bridge: Intel Corporation 82371AB/EB/MB PIIX4 ACPI (rev 03)
00:02.0 VGA compatible controller: Cirrus Logic GD 5446
00:03.0 Ethernet controller: Red Hat, Inc Virtio network device
00:04.0 Infiniband controller: Mellanox Technologies MT27700 Family [ConnectX-4 Virtual Function]
00:05.0 Unclassified device [00ff]: Red Hat, Inc Virtio memory balloon
[root@sandy1:migration]$
[root@sandy1:migration]$
[root@sandy1:migration]$
[root@sandy1:migration]$
[root@sandy1:migration]$
[root@sandy1:migration]$virsh migrate --live --rdma-pin-all --migrateuri rdma://sandy3-ib sandy1-vm1 qemu://sandy3-ib/system
error: Requested operation is not valid: domain has assigned non-USB host devices

[root@sandy1:migration]$
```

Overview of Existing Migration Solutions for SR-IOV

	Platform	NIC	No Guest OS Modification	Device Driver Independent	Hypervisor Independent
Zhai, etc (Linux bonding driver)	Ethernet	N/A	Yes	No	Yes (Xen)
Kadav, etc (shadow driver)	Ethernet	Intel Pro/1000 gigabit NIC	No	Yes	No (Xen)
Pan, etc (CompSC)	Ethernet	Intel 82576, Intel 82599	Yes	No	No (Xen)
Guay, etc	InfniBand	Mellanox ConnectX2 QDR HCA	Yes	No	Yes (Oracle VM Server (OVS) 3.0.)
Han	Ethernet	Huawei smart NIC	Yes	No	No (QEMU+KVM)
Xu, etc (SRVM)	Ethernet	Intel 82599	Yes	Yes	No (VMware EXSi)

Can we have a hypervisor-independent and device driver-independent solution for InfiniBand based HPC Clouds with SR-IOV?

Problem Statement

- Can we propose a realistic approach to solve this contradiction with some tradeoffs?
- Most HPC applications are based on MPI runtime nowadays, can we propose a VM migration approach for MPI applications over SR-IOV enabled InfiniBand clusters?
- Can such a migration approach for MPI applications avoid modifying hypervisors and InfiniBand drivers?
- Can the proposed design migrate VMs with SR-IOV IB devices in a high-performance and scalable manner?
- Can the proposed design minimize the overhead for running MPI applications inside the VMs during migration?

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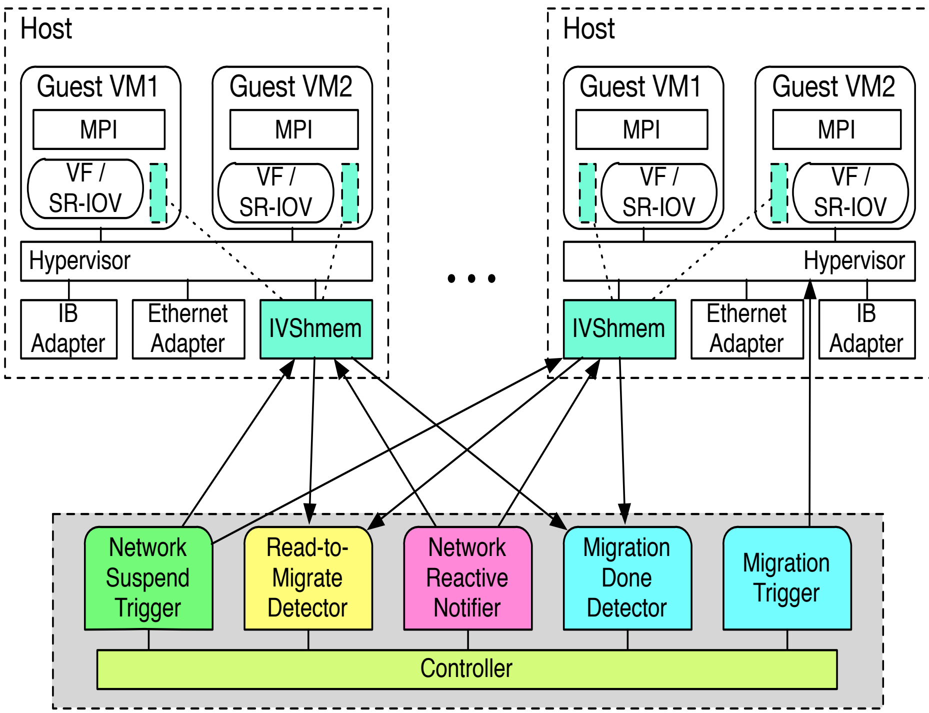
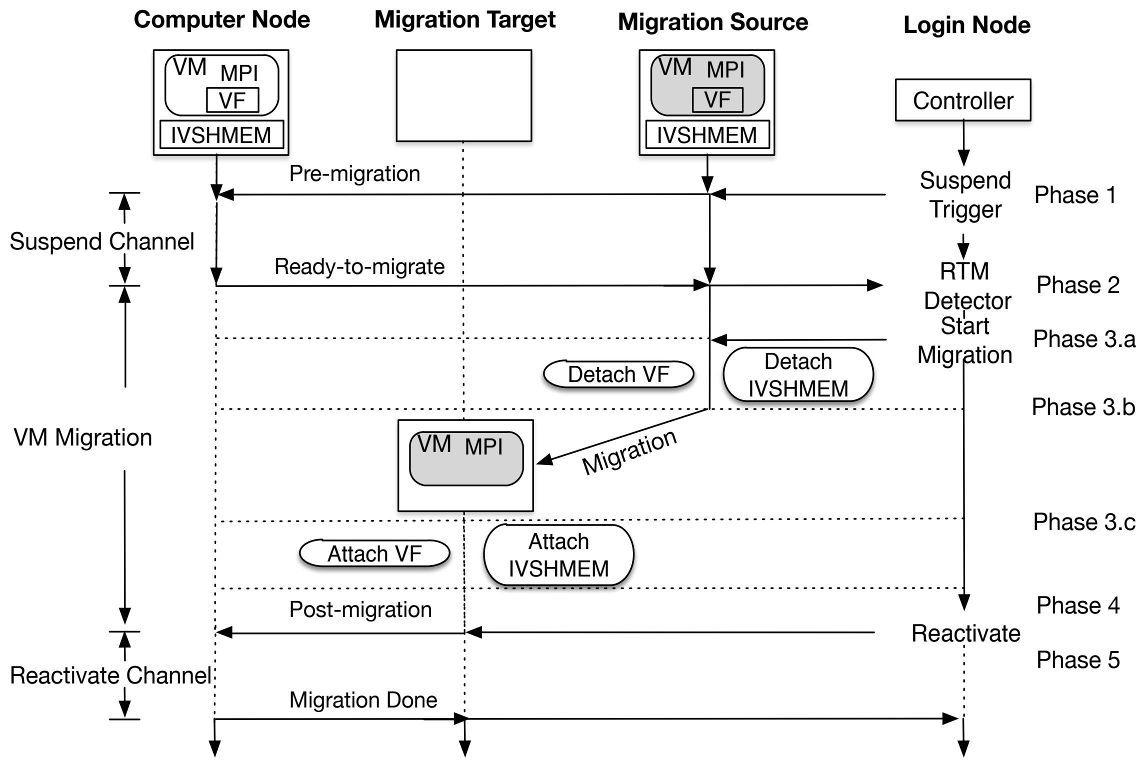
Proposed High Performance SR-IOV enabled VM Migration Framework



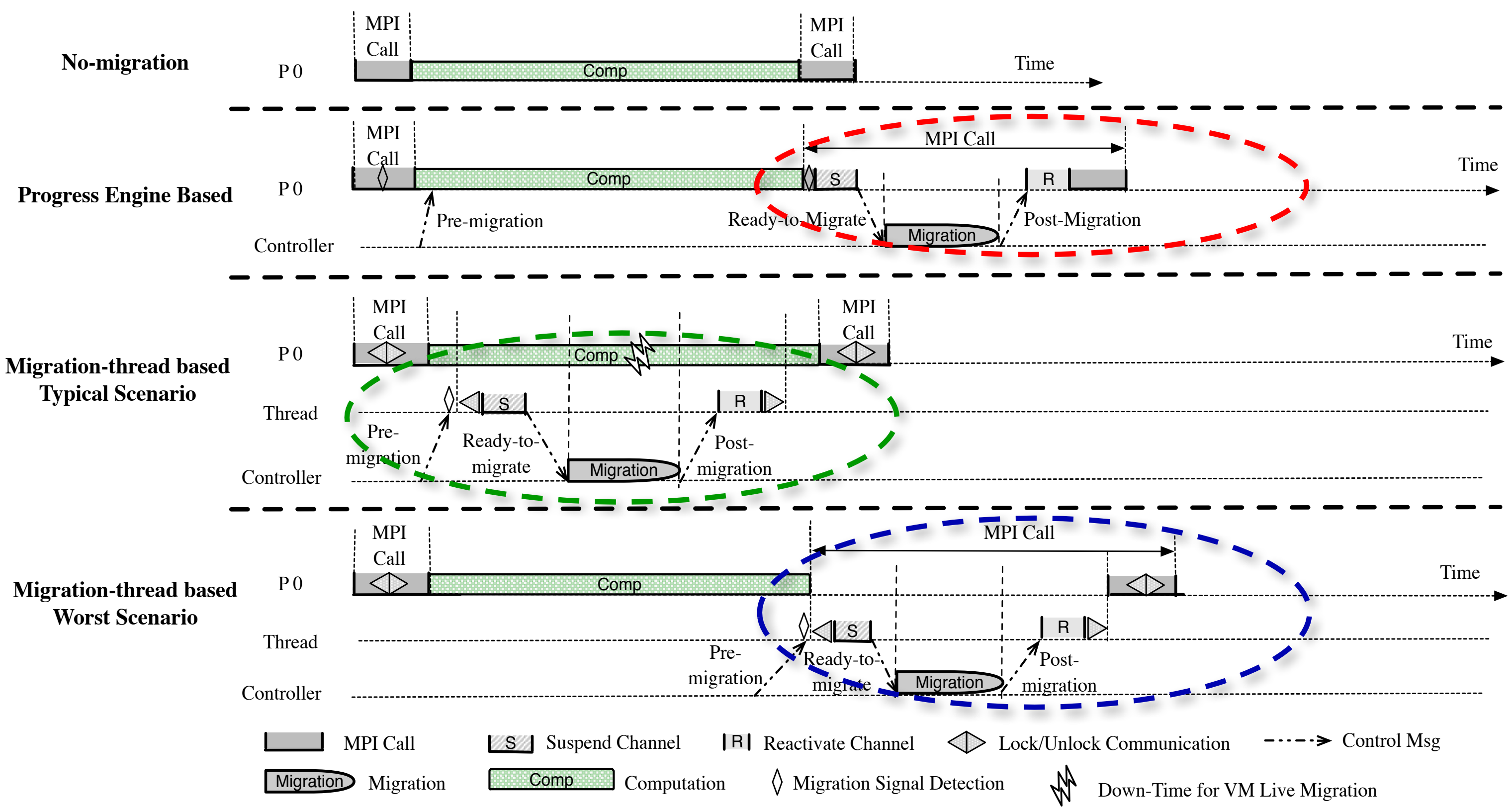
- Two challenges need to handle:
  - Detachment/re-attachment of virtualized IB device
  - Maintain IB connection
- Multiple parallel libraries to coordinate VM during migration (detach/reattach SR-IOV/IVShmem, migrate VMs, migration status)
- MPI runtime handles the IB connection suspending and reactivating
- Propose Progress Engine (**PE**) and Migration Thread based (**MT**) design to optimize VM migration and MPI application performance

J. Zhang, X. Lu, D. K. Panda. High-Performance Virtual Machine Migration Framework for MPI Applications on SR-IOV enabled InfiniBand Clusters. IPDPS, 2017

Sequence Diagram of VM Migration



Proposed Design of MPI Runtime



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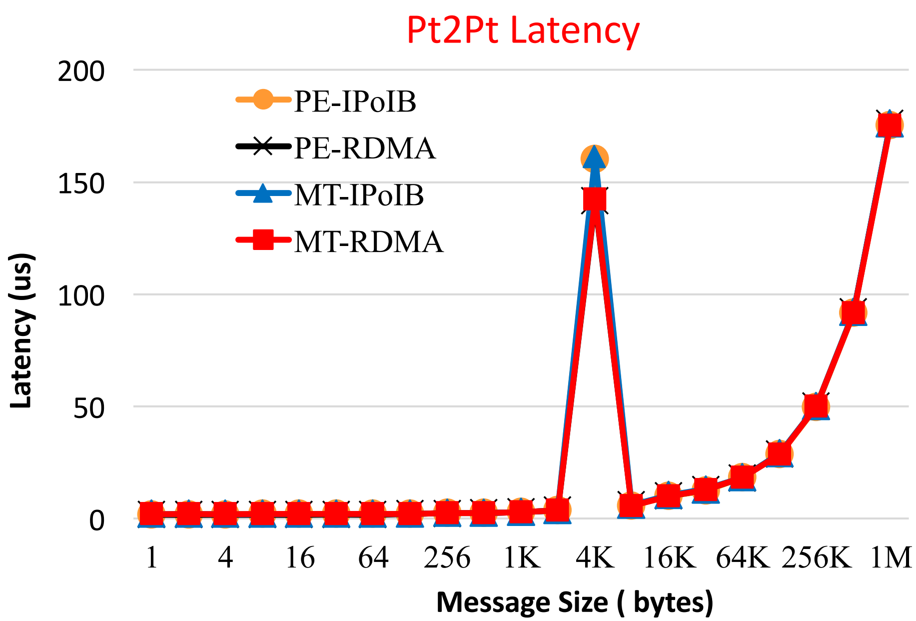
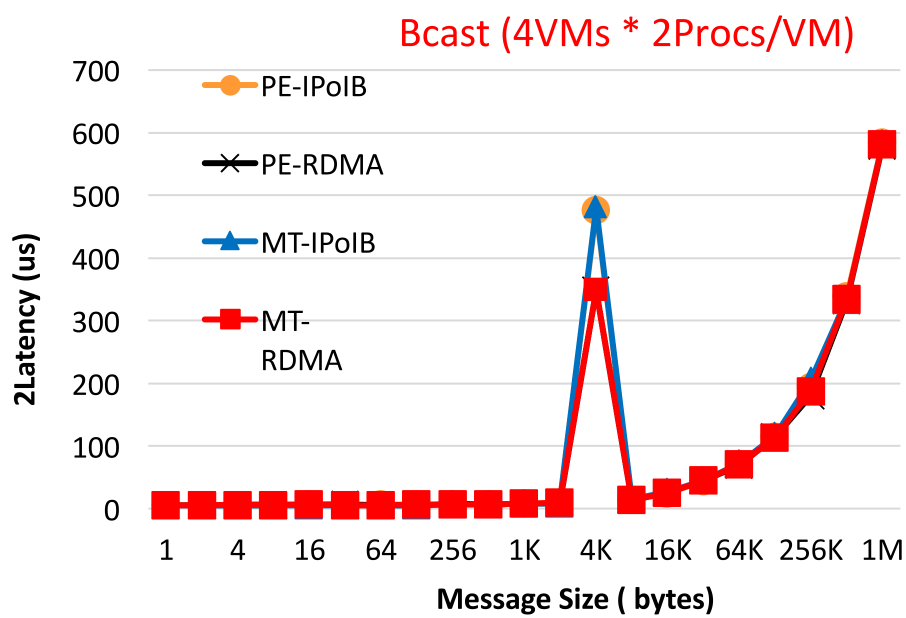
Experimental Testbed

Cluster	Chameleon Cloud	Nowlab
CPU	Intel Xeon E5-2670 v3 24-core 2.3 GHz	Intel Xeon E5-2670 dual 8-core 2.6 GHz
RAM	128 GB	32 GB
Interconnect	Mellanox ConnectX-3 HCA, (FDR 56Gbps), MLNX OFED LINUX-3.0-1.0.1 as driver	Mellanox ConnectX-3 HCA, (FDR 56Gbps), MLNX OFED LINUX-3.2-2.0.0
OS	CentOS Linux release 7.1.1503 (Core)	
Compiler	GCC 4.8.3	
	MVAPICH2 and OSU micro-benchmarks v5.3	

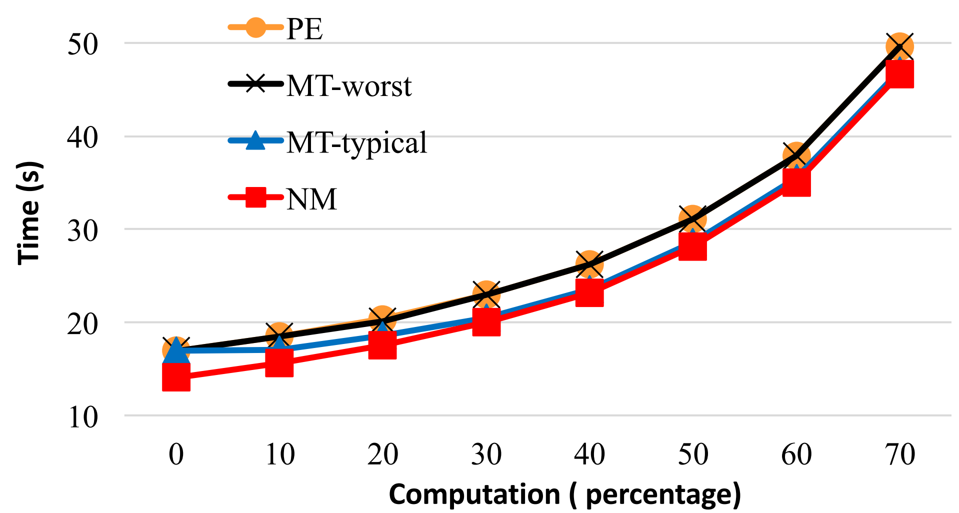
Point-to-Point and Collective Performance





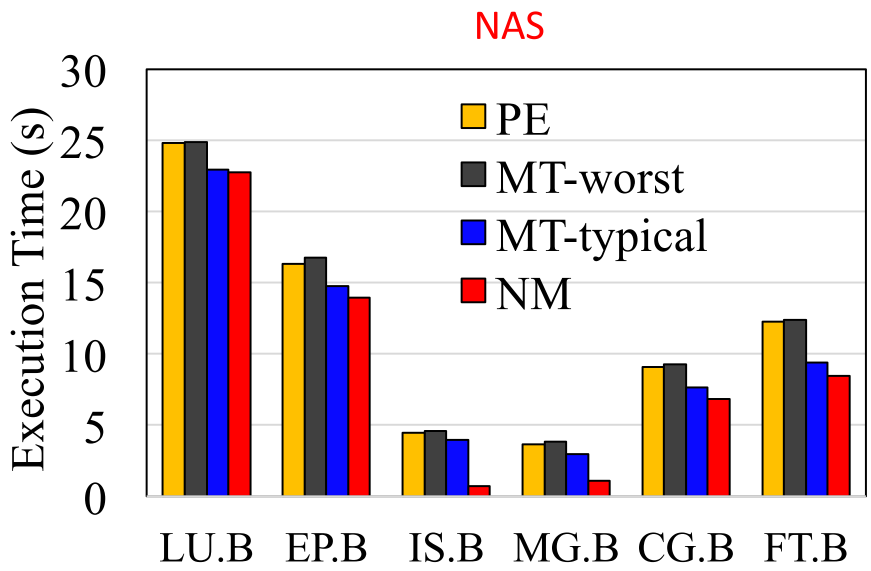
- Migrate a VM from one machine to another while benchmark is running inside
- Proposed MT-based designs perform slightly worse than PE-based designs because of lock/unlock
- No benefit from MT because of NO computation involved

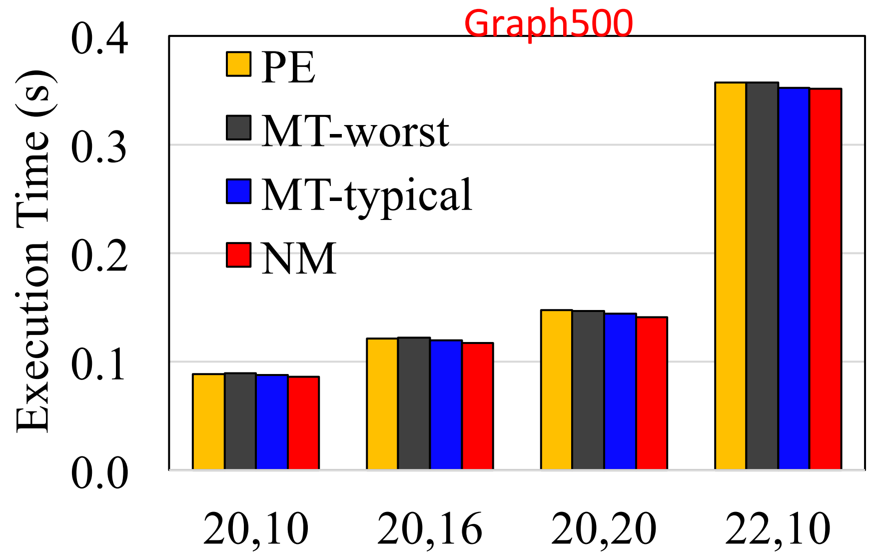
Overlapping Evaluation



- fix the communication time and increase the computation time
- 10% computation, partial migration time could be overlapped with computation in MT-typical
- As computation percentage increases, more chance for overlapping

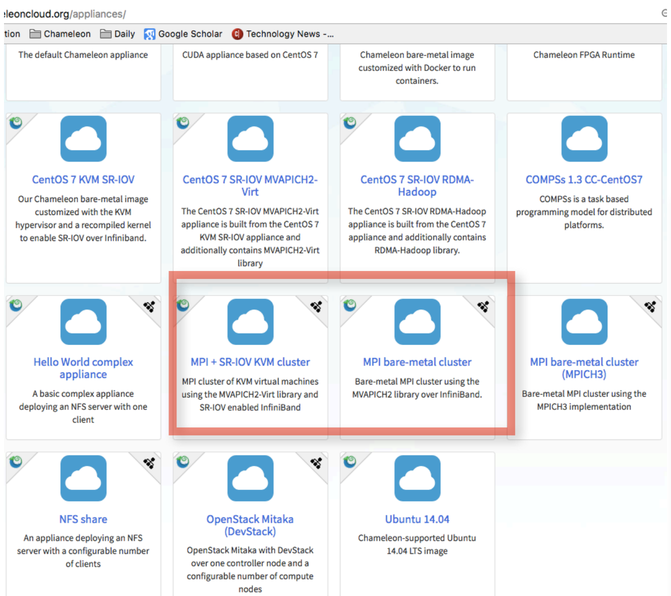
Application Performance





- 8 VMs in total and 1 VM carries out migration during application running
- Compared with NM, MT- worst and PE incur some overhead
- MT-typical allows migration to be completely overlapped with computation

Available Appliances on Chameleon Cloud*

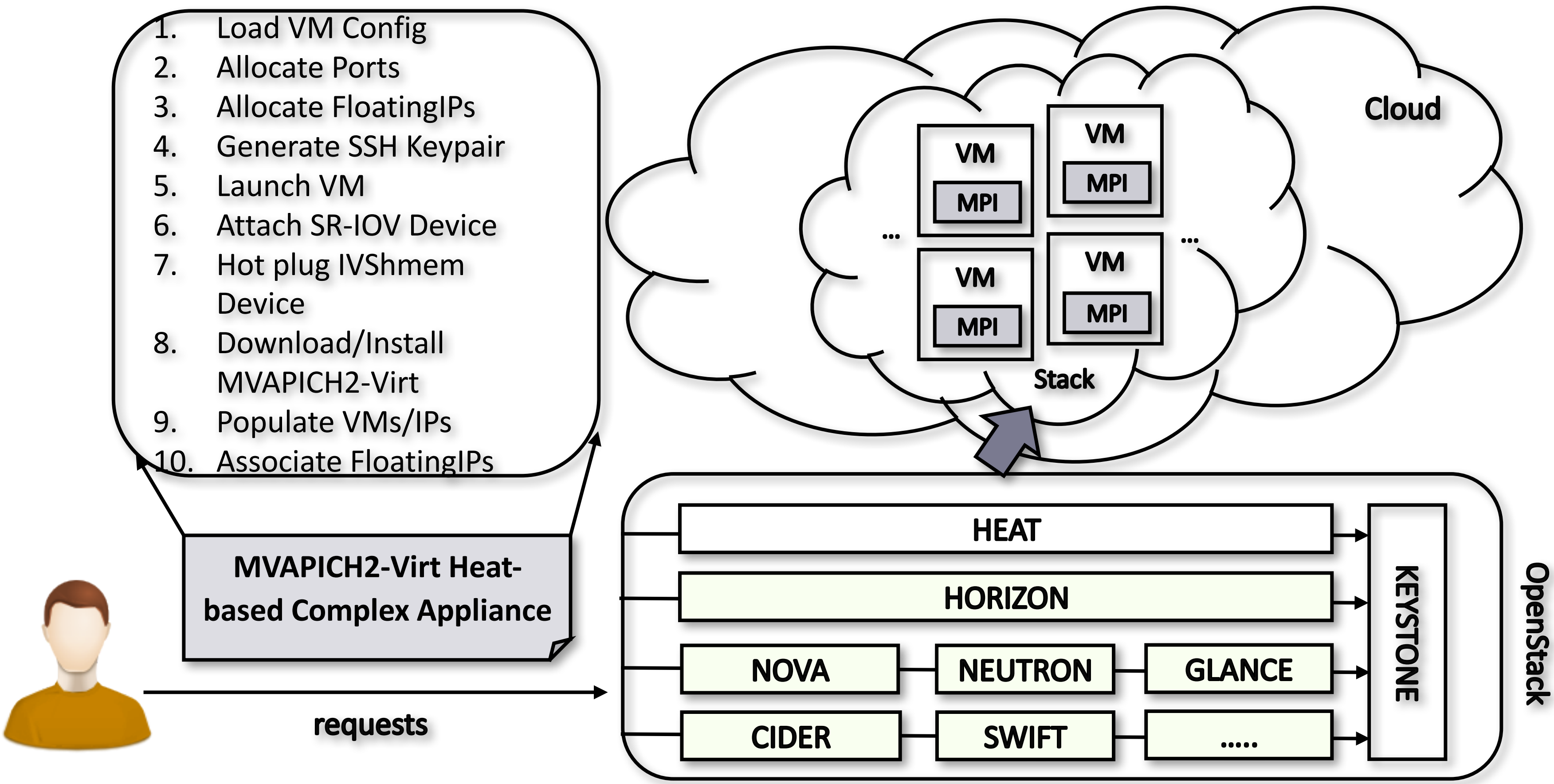


Appliance	Description
CentOS 7 KVM SR-IOV	Chameleon bare-metal image customized with the KVM hypervisor and a recompiled kernel to enable SR-IOV over InfiniBand. https://www.chameleoncloud.org/appliances/3/
MPI bare-metal cluster complex appliance (Based on Heat)	This appliance deploys an MPI cluster composed of bare metal instances using the MVAPICH2 library over InfiniBand. https://www.chameleoncloud.org/appliances/29/
MPI + SR-IOV KVM cluster (Based on Heat)	This appliance deploys an MPI cluster of KVM virtual machines using the MVAPICH2-Virt implementation and configured with SR-IOV for high-performance communication over InfiniBand. https://www.chameleoncloud.org/appliances/28/
CentOS 7 SR-IOV RDMA-Hadoop	The CentOS 7 SR-IOV RDMA-Hadoop appliance is built from the CentOS 7 appliance and additionally contains RDMA-Hadoop library with SR-IOV. https://www.chameleoncloud.org/appliances/17/

- Through these available appliances, users and researchers can easily deploy HPC clouds to perform experiments and run jobs with
  - High-Performance SR-IOV + InfiniBand
  - High-Performance MVAPICH2 Library over bare-metal InfiniBand clusters
  - High-Performance MVAPICH2 Library with Virtualization Support over SR-IOV enabled KVM clusters
  - High-Performance Hadoop with RDMA-based Enhancements Support

[*] Only include appliances contributed by OSU NowLab

MPI Complex Appliances based on MVAPICH2 on Chameleon



Conclusion & Future Work

- Propose a high-performance VM migration framework for MPI applications on SR- IOV enabled InfiniBand clusters
- Hypervisor- and InfiniBand driver-independent
- Design Progress Engine (PE) based and Migration Thread (MT) based MPI runtime design
- Design a high-performance and scalable controller which works seamlessly with our proposed designs in MPI runtime
- Evaluate the proposed framework with MPI level micro-benchmarks and real-world HPC applications
- Could completely hide the overhead of VM migration through computation and migration overlapping
- Future Work – Evaluate our proposed framework at larger scales and different hypervisors, such as Xen; Solution will be available in upcoming release

Thank You!

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Network-Based Computing Laboratory
http://nowlab.cse.ohio-state.edu/