CPSL

Cyber-Physical Systems Laboratory

RT-Xen: Real-Time Virtualization for the Cloud

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Real-Time Virtualization

- Cars are becoming real-time mini-clouds!
  - ❑ Consolidate 100 ECUs → 10 multicore processors.
  - ❑ Integrate multiple vendors' systems → common platforms.
  - ❑ Must preserve real-time guarantees on a virtualized platform!

- Internet of Things → Cyber-Physical Systems
  - ❑ Smart manufacturing, smart transportation, smart grid.
  - ❑ Internet-scale sensing and control → real-time cloud computing.

- Cloud gaming
  - ❑ Xbox One: cloud offloading computation of environmental elements
  - ❑ Sony acquired Gaikai, an open cloud gaming platform.

Virtualization is *not* real-time today

- Existing hypervisors provide no guarantee on latency
  - ❑ Xen: credit scheduler, [credit, cap]
  - ❑ VMware ESXi: [reservation, share, limitation]
  - ❑ Microsoft Hyper-V: [reserve, weight, limit]
- Public clouds lack service level agreement on latency
  - ❑ EC2, Compute Engine, Azure: #VCPUs

Current platforms provision CPU resources, not real-time performance!

Challenges

- Support real-time applications in a virtualized environment.
  - Latency *guarantees* to tasks running in virtual machines (VMs).
  - Real-time performance *isolation* between VMs.

- Real-time performance provisioning at different levels
  - Virtualization within a host
  - Communication and I/O
  - Cloud resource management

RT-Xen

- Real-time hypervisor based on Xen
  - ❑ Real-time VM scheduling
  - ❑ Real-time communication
- Build on compositional scheduling theory
  - ❑ VMs specify resource interfaces
  - ❑ Real-time guarantees to tasks in VMs
- Open source
  - ❑ Xen patch in progress

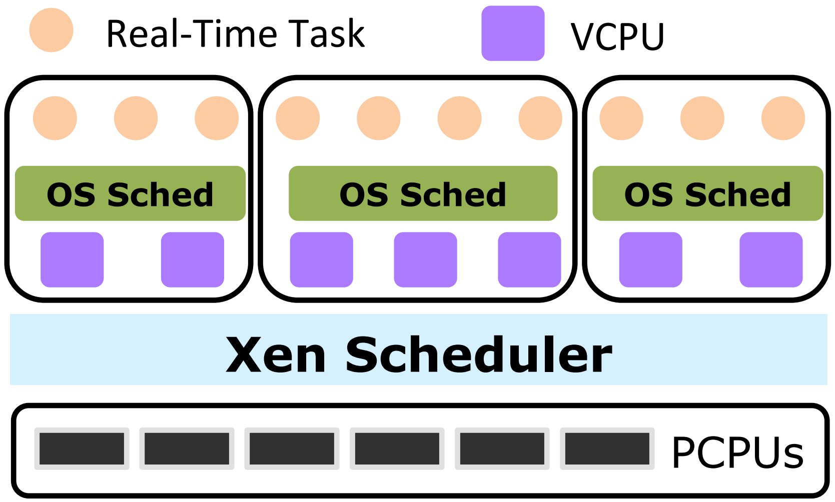
RT-Xen

Real-Time Virtualization

- RT-OpenStack: cloud management based on RT-Xen

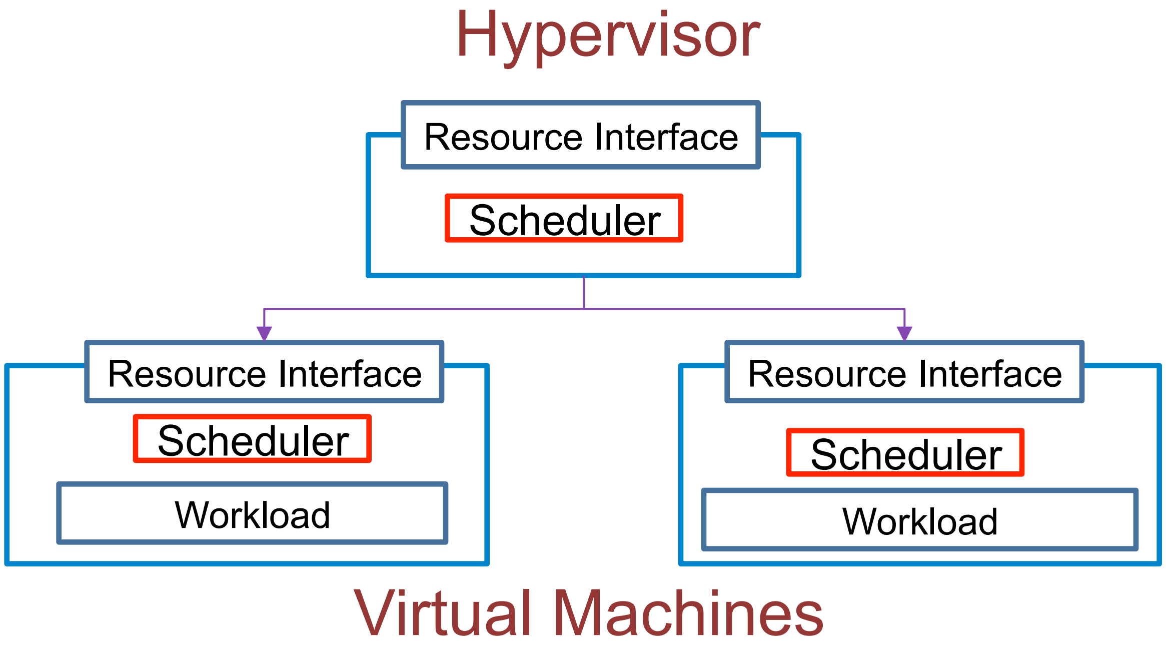
Xen Virtualization Architecture

- Xen: type-1, baremetal hypervisor
  - Domain-0: drivers, tool stack to control VMs.
  - Guest Domain: para-virtualized or fully virtualized OS.
- Xen scheduler
  - Guest OS runs on VCPUs.
  - Xen schedules VCPUs on PCPUs.
  - Credit scheduler: round-robin with proportional share.



Compositional Scheduling

- Analytical real-time guarantees to tasks running in VMs.
- VM resource interfaces
  - Hides task-specific information
  - Multicore: <period, budget, #VCPU>
  - Computed based on compositional scheduling analysis

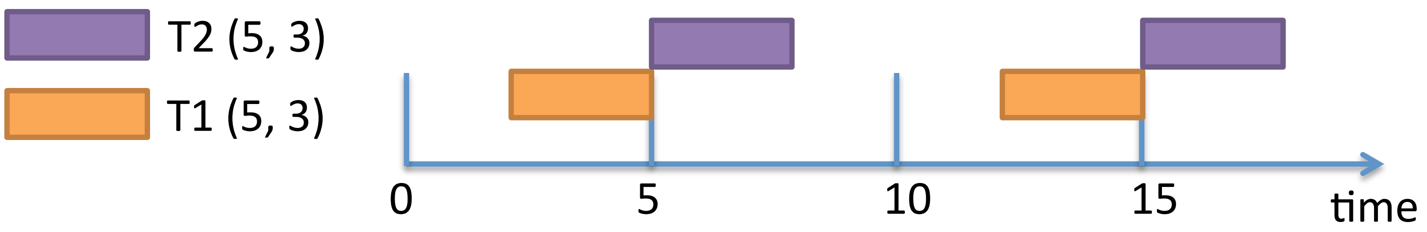


Real-Time Scheduling Policies

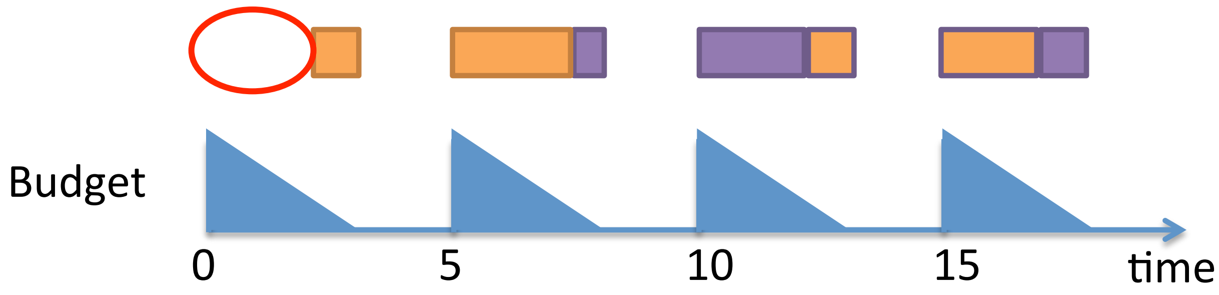
- Priority schemes
  - ❑ Static priority: Rate Monotonic
  - ❑ Dynamic priority: Earliest Deadline First (EDF)

- Multi-core
  - ❑ Global scheduling: allow VCPU migration across cores
  - ❑ Partitioned scheduling: bound VCPUs to cores

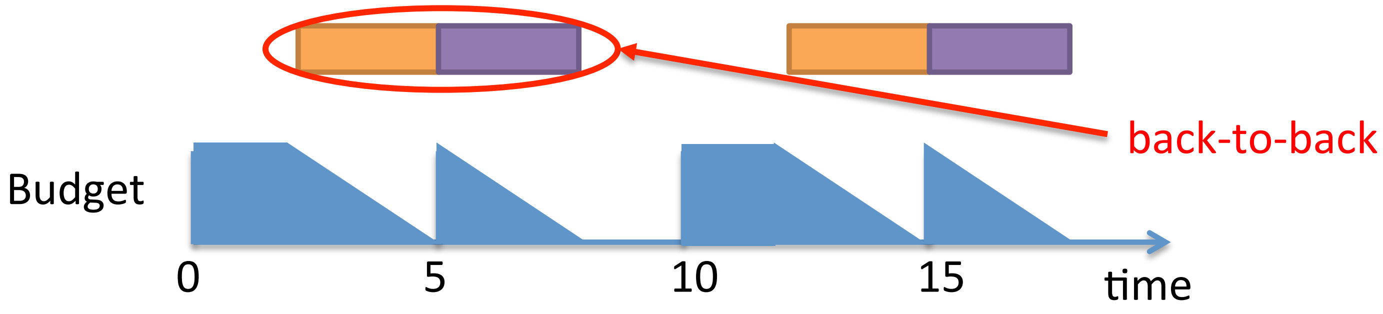
Scheduling VM as "Server"



Periodic Server (5,3)

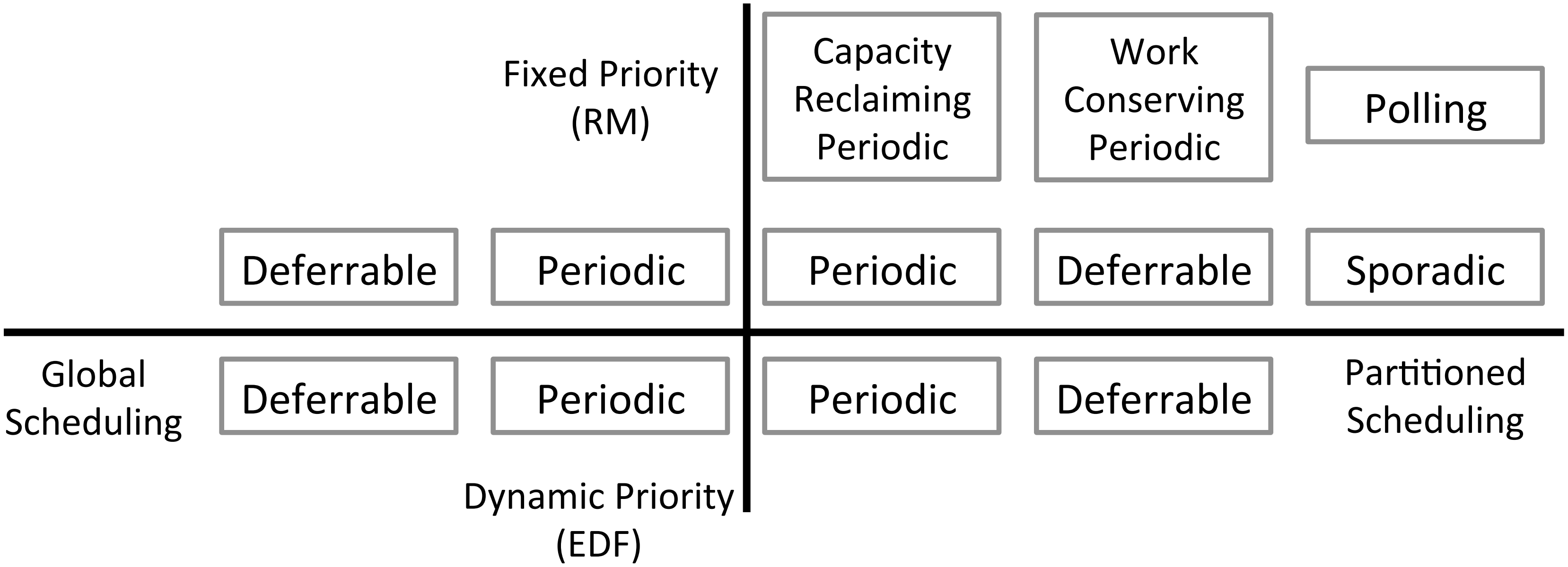


Deferrable Server (5,3)



RT-Xen: Real-Time Scheduling in Xen

- Single-core RT-Xen 1.0
- Single-core enhanced RT-Xen 1.1
- Multi-core scheduling RT-Xen 2.0
  - ❑ RT-global
  - ❑ RT-partition



Fixed Priority (RM)

Capacity Reclaiming Periodic

Work Conserving Periodic

Polling

Deferrable

Periodic

Periodic

Deferrable

Sporadic

Global Scheduling

Deferrable

Periodic

Periodic

Deferrable

Partitioned Scheduling

Dynamic Priority (EDF)

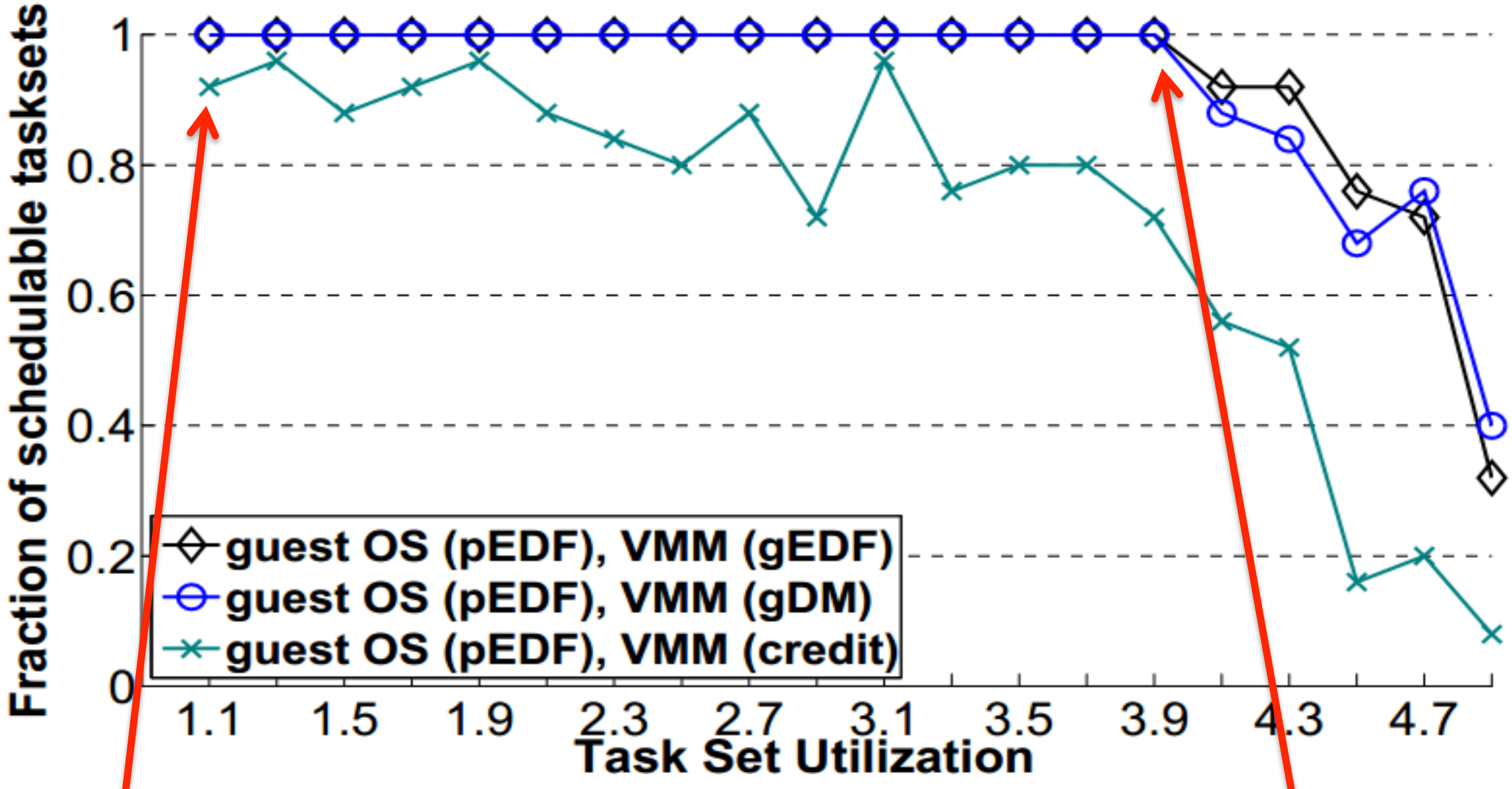
Experimental Setup

- Hardware: Intel i7 processor, 6 cores, 3.33 GHz
  - Allocate 1 VCPU for Domain-0, pinned to PCPU 0
  - All guest VMs use the remaining cores

- Software
  - Xen 4.3 patched with RT-Xen
  - Guest OS: Linux patched with LITMUS

- Workload
  - Period tasks: synthetic, ARINC 653 avionics workload (RT-Xen 1.1)
  - Allocate tasks → VMs

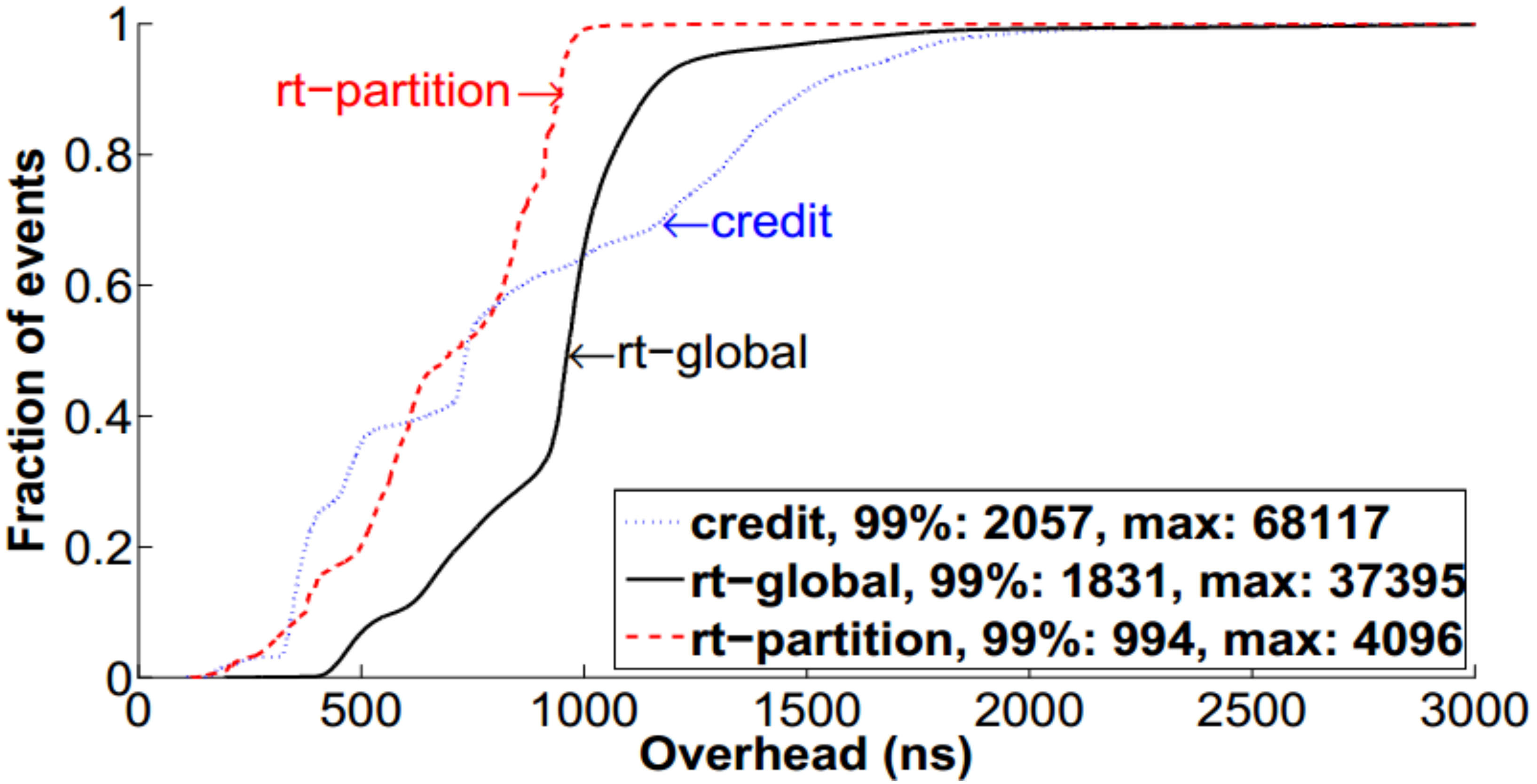
RT-Xen 2.0: Credit Scheduler



- Credit misses deadlines at 22%/CPU utilization.

- RT-Xen delivers real-time performance at 78%/CPU utilization.

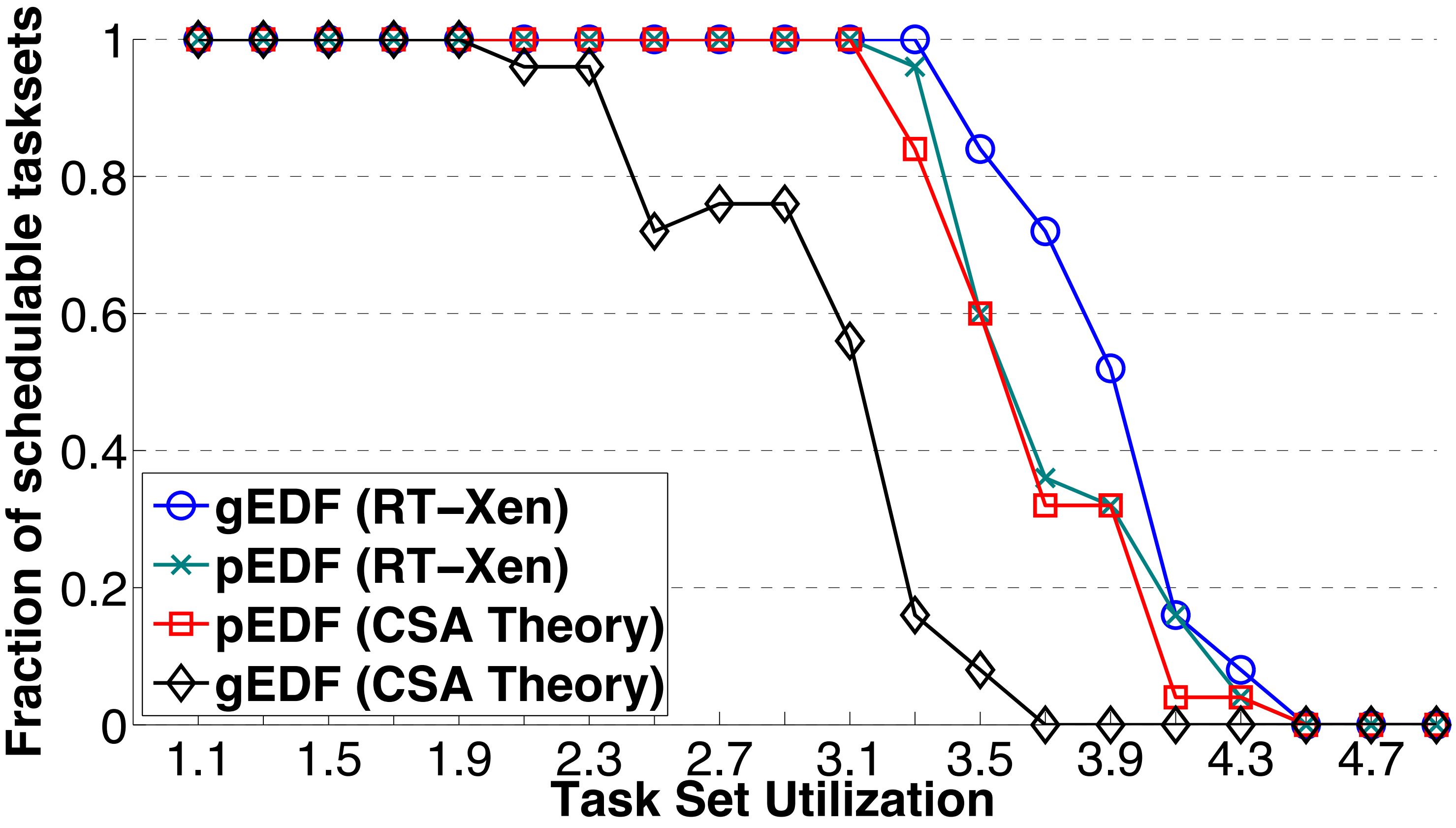
RT-Xen 2.0: Scheduling Overhead



- rt-global has extra overhead due to global lock.

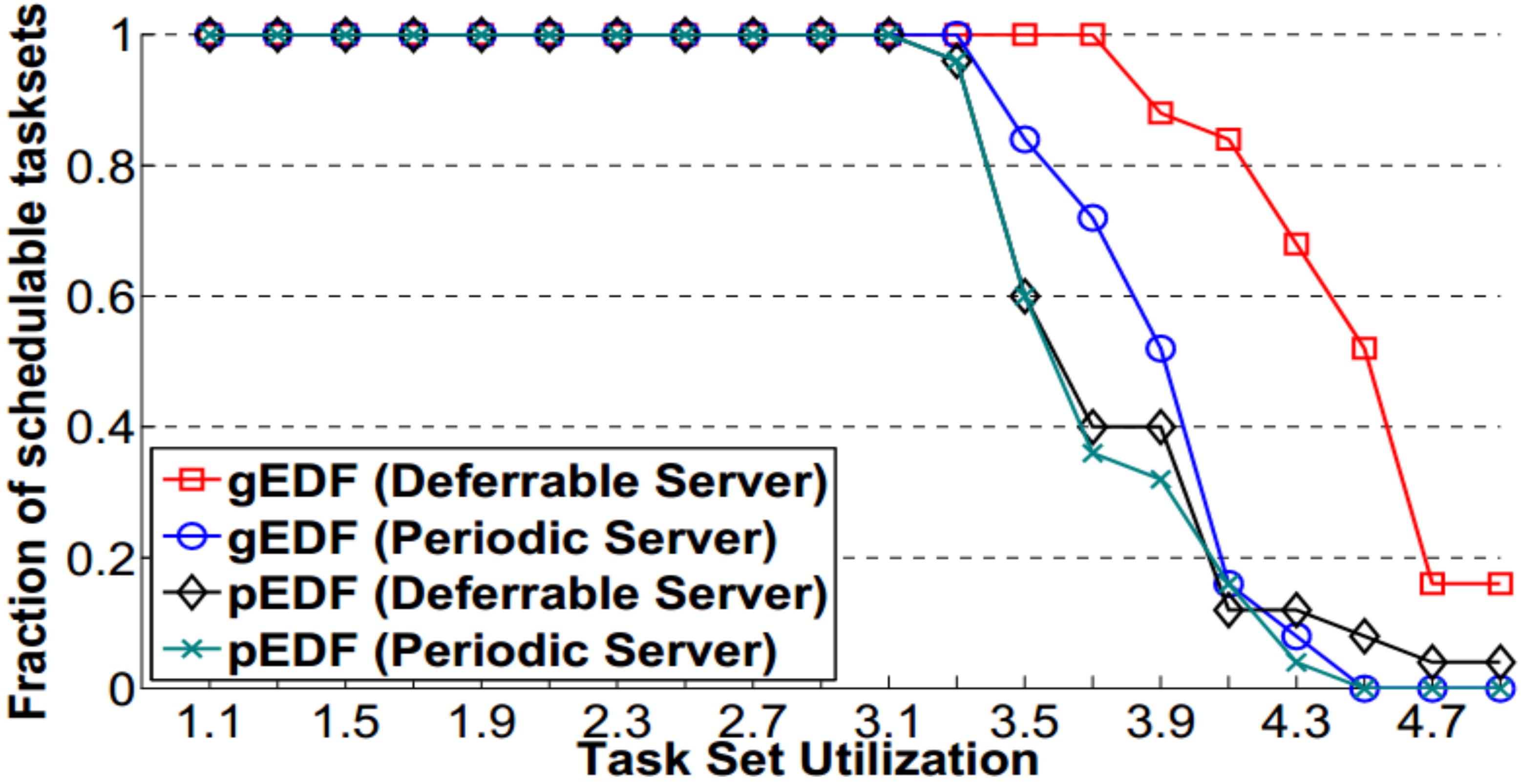
- Credit has poor max overhead due to load balancing.

RT-Xen 2.0: Theory vs. Experiments



- gEDF > pEDF empirically, thanks to work-conserving global scheduling.
- gEDF < pEDF theoretically due to pessimistic analysis.

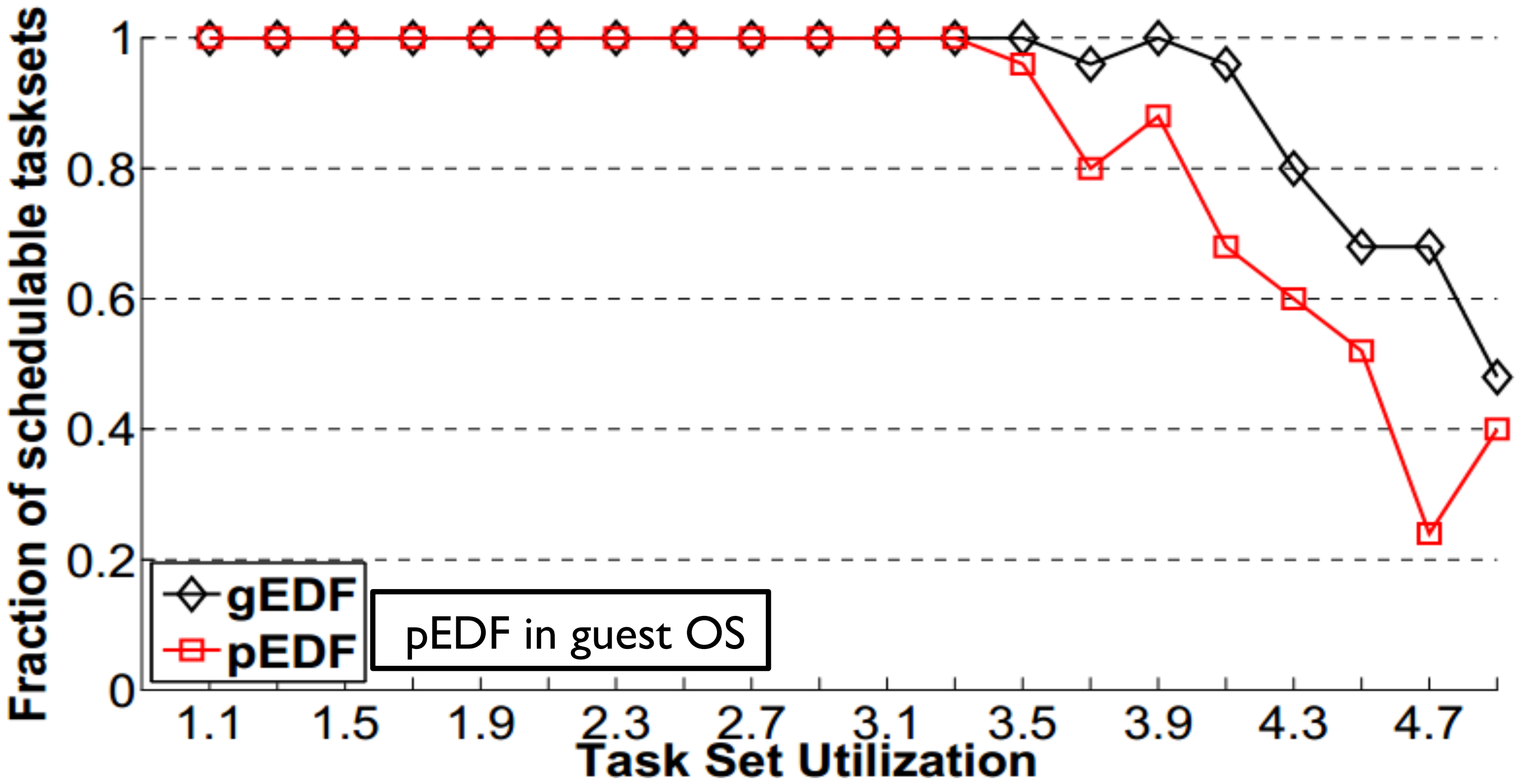
RT-Xen 2.0: Deferrable vs. Periodic



Work-conserving wins empirically!

- Deferable Server (DS) > Periodic Server.
- gEDF+DS → best real-time performance.

RT-Xen 2.0: How about Cache?



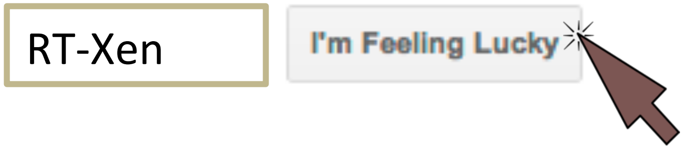
pEDF in guest OS

- gEDF > pEDF for cache intensive workload.
- Benefit of global scheduling dominates migration cost.
- Shared cache mitigates cache penalty due to migration.

Conclusion

- Diverse applications demand real-time virtualization and cloud.
  - ❑ Embedded real-time systems
  - ❑ Internet-scale cyber-physical systems
  - ❑ Latency-sensitive cloud applications
- RT-Xen provides real-time performance and guarantees
  - ❑ Efficient implementation of diverse real-time scheduling policies.
  - ❑ Leverage compositional scheduling theory → analytical guarantee.
  - ❑ Resource interface → systematic resource allocation for latency bounds.
- On-going
  - ❑ Working on RT-Xen patch for Xen core distribution.
  - ❑ RT-OpenStack: integration with OpenStack on the way.

Check out RT-Xen


RT-Xen

RT-Xen

Real-Time Virtualization

https://sites.google.com/site/realtimexen/

- **RT-Xen 1.0**: S. Xi, J. Wilson, C. Lu, and C.D. Gill, RT-Xen: Towards Real-Time Hypervisor Scheduling in Xen, ACM International Conferences on Embedded Software (EMSOFT), 2011.
- **RT-Xen 1.1:** J. Lee, S. Xi, S. Chen, L.T.X. Phan, C. Gill, I. Lee, C. Lu and O. Sokolsky Realizing Compositional Scheduling through Virtualization, IEEE Real-Time and Embedded Technology and Applications Symposium (RTAS), 2012
- **RT-Xen 2.0**: S. Xi, C. Lu, C. Gill, M. Xu, L.T.X. Phan, I. Lee, and O. Sokolsky, Real-Time Multi-Core Virtual Machine Scheduling in Xen, Washington University Technical Report, WUCSE-2013-109 2013
- **inter-domain communication**: S. Xi, C. Li, C. Lu, and C. Gill, Prioritizing Local Inter-Domain Communication in Xen, ACM/IEEE International Symposium on Quality of Service (IWQoS), 2013.