Real-Time Cloud Computing

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Internet of Things

Convergence of

- **Miniaturized hardware**: integrate processor, sensors and radios.
- **Low-power wireless**: connect millions of devices to the Internet.
- **Data analytics**: make sense of sensor data.
- **Cloud**: scalable computing.

Internet of Things

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IoT-Driven Control

- Internet of Things → large-scale real-time control
  - Smart manufacturing, smart transportation, smart grid…
  - Need **real-time cloud computing** for IoT!

- Example: Intelligent Transportation
  - Collect data from cameras and roadside detectors.
  - Analyze traffic dynamics and optimize traffic signals.
  - Control traffic signals.
  - SCATS @ Sydney: controlling 3,400 signals at 1s round-trip latency.
Embedded System Virtualization

- Consolidate 100 ECUs $\rightarrow$ ~10 multicore processors.
- Integrate multiple systems on a common platform.
  - Infotainment on Linux or Android
  - Safety-critical control on AUTOSAR
- Preserve real-time performance on a virtualized platform!

Cloud is real-time today

- Virtualization platforms provide no guarantee on latency
  - Xen: credit scheduler, [credit, cap]
  - VMware ESXi: [reservation, share, limitation]
  - Microsoft Hyper-V: [reserve, weight, limit]

- Clouds lack service level agreement on latency
  - Amazon, Google, Microsoft cloud services: #VCPUs

Current clouds provision resources, not latency!
Towards Real-Time Cloud

- Support real-time applications in the cloud.
  - Latency guarantees for tasks running in virtual machines (VMs).
  - Real-time performance isolation between VMs.
  - Resource sharing between real-time and non-real-time VMs.

- Multi-level real-time performance provisioning.
  - RT-Xen → real-time VM scheduling on a virtualized host.
  - VATC → real-time network I/O on a virtualized host.
  - RT-OpenStack → real-time cloud resource management.
Xen

- **Xen**: type-1, baremetal hypervisor
  - Domain-0: drivers, tool stack to control VMs.
  - Guest Domain: para-virtualized or fully virtualized OS.

- **Scheduling hierarchy**
  - Xen schedules VCPUs on PCPUs.
  - Guest OS schedules threads on VCPUs.
  - Xen credit scheduler: round-robin with proportional share.
RT-Xen

- Real-time schedulers in the Xen hypervisor.
- Provide real-time guarantees to tasks in VMs.
- Incorporated in **Xen 4.5** as the real-time scheduler.

Compositional Scheduling

- Analytical real-time guarantees to tasks running in VMs.
- VM resource interfaces
  - A set of VCPUs each with resource demand $<\text{period, budget}>$
  - Hides task-specific information
  - Computed based on compositional scheduling analysis

Diagram:
- Hypervisor
  - Resource Interface
  - Scheduler
  - Workload
- Virtual Machines
  - Resource Interface
  - Scheduler
  - Workload
Real-Time Scheduler Design

- Global scheduling
  - Allow VCPU migration across cores
  - Work conserving – utilize any available cores
  - Migration overhead and cache penalty

- Partitioned scheduling
  - Assign and bind VCPUs to cores
  - Cores may idle when others have work pending
  - No migration overhead or cache penalty

- Enforce resource interface through budget management
  - Periodic server vs. deferrable server

- Priority: Earliest Deadline First vs. Deadline Monotonic
• Xen misses deadlines at 22% of CPU capacity.

• RT-Xen delivers real-time performance at 78% of CPU capacity.
Virtualized Network I/O

- Xen handles all network traffic through Dom0
- Real-time and non-real-time traffic share Dom0
  - CPU and network contention
- Long delays for real-time traffic in virtualized hosts
Network I/O in Virtualized Hosts

- Linux Queueing Discipline
  - Rate-limit and shape flows
  - Prioritization or fair packet scheduling

- Priority inversion in virtualization components
  - between transmissions
  - between transmission and reception

- VATC: Virtualization-Aware Traffic Control
  - Process packets in prioritized kernel threads
  - Dedicated packet queues per priority

Real-Time Traffic Latency

VATC reduces priority inversion $\Rightarrow$ lower latency for real-time traffic.

- Median round-trip latency of real-time traffic.
- CPU contention from two small-packet interfering streams.
Virtualized Host ➔ Cloud

- Provide real-time performance to real-time VMs
- Achieve high resource utilization
OpenStack Limitations

- Popular open-source cloud management system

- VM resource interface
  - Number of VCPUs
  - Not real-time

- VM-to-host mapping
  - Filtering (admission control)
    - VCPU-to-PCPU ratio (16:1), max VMs per host (50)
    - Coarse-grained admission control for CPU resources
  - Ranking (VM allocation)
    - Balance memory usage
    - No consideration of CPU resources
RT-OpenStack

- Co-hosting real-time VMs with non-real-time VMs

- Deliver real-time performance
  - Support RT-Xen resource interface
  - Real-time-aware VM-to-host mapping

- Achieve high resource utilization
  - Co-locate non-real-time VMs with real-time VMs
  - Non-real-time VMs consume remaining resources *without* affecting the real-time performance of real-time VMs

RT-OpenStack: VM-to-Host Mapping

- Admission control: RT-Filter
  - Accept real-time VMs based on schedulability and memory
  - Consider only accepted real-time VMs

- VM allocation: RT-Weigher
  - Balance CPU utilization
  - Consider only accepted real-time VMs

<table>
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<tr>
<th>Resource Interface</th>
<th>Admission Control</th>
<th>VM Allocation</th>
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<tr>
<td>Real-Time VMs</td>
<td>{&lt;period, budget&gt;}</td>
<td>Schedulability + Memory</td>
</tr>
<tr>
<td>Non-Real-Time VMs</td>
<td>Best Effort</td>
<td>Memory</td>
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OpenStack

- Overload four hosts with real-time VMs → deadline misses.
- Two hosts running non-real-time VMs only.
- Unbalanced distribution of real-time domains.

![Graph showing CPU utilization](image)
Schedulability guarantees for real-time VMs → no deadline miss.
Distribute real-time VMs across hosts.
Hadoop makes progress using remaining CPU resources.

Hadoop finish time: 435 seconds
Real-time Cloud Stack

- **RT-Xen**: real-time VM scheduling in virtualized hosts.
- **VATC**: real-time network I/O in virtualized hosts.
- **RT-OpenStack**: real-time cloud resource management.
End-to-End Real-Time for IoT

- Miniaturized hardware → real-time embedded systems
- Low-power wireless → real-time wireless
- Data analytics → real-time analytics
- Cloud → real-time service chains from edge to cloud

Large-Scale IoT-driven Control
→ Smart Manufacturing, City, Grid…