Time Capsule: Tracing Packet Latency across Different Layers in Virtualized Systems

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Virtualization and Multi-Tenancy

• Mainstream in data centers
  ✓ Fault isolation and enhanced security
  ✓ Improved hardware utilization

• Challenging to guarantee QoS
  ✓ Complex virtualization stacks
  ✓ Performance interference

Latency-sensitive network apps suffer poor and unpredictable performance
Para-virtualized Network I/O

Physical machine

Privileged domain
- Virtual Switch
- Native Driver
- Backend Driver

Guest
- App
- Frontend Driver

Shared Memory

Hypervisor

NIC

Hardware

Physical interrupt

Virtual interrupt

Protection domain

Cross-machine communication
Possible Causes of Long Latency

• Additional layers of software stack
  ✓ Asynchronous notifications
  ✓ Data copy

• Resource contention
  ✓ Time-sharing CPU
  ✓ Contentions on data structures, e.g., locks and queues

• Packet transmission in DC network

End-to-end latency monitoring and analysis is key to identifying the causes
Challenges in Monitoring Packet Latency in Virtualized Systems

- Across the **boundaries** of protection domains
  - Machines, privileged domains, guests, and hypervisor
- **Correlating events** in various components
  - Asynchronous packet processing
- **Fine-grained** tracing with **low overhead**
  - Troubleshooting at packet level
- **Application transparency**
  - A wide spectrum of network apps, no access to code
Related Work

• Tracing tools
  ✓ App: gperf
  ✓ OS: SystemTap, Dtrace, Perf, and bcc
  ✓ Hypervisor: Xentrace

• Distributed tracing
  ✓ Causal tracing: Pip [NSDI’06], X-Trace [NSDI’07], Dapper [Google], Fay [SOSP’11], Magpie [HotOS]
  ✓ Log mining: Draco [DSN’12], [Nagaraj NSDI’12], [Xu SOSP’09]
Related Work (cont’)

• Tracing metadata propagation
  ✓ Pivot Tracing [SOSP’15], X-Trace [NSDI’07], Dapper[Google]
  ✓ Propagating task IDs and timestamps using task containers or embedding the info into protocol headers

Tracing virtualized network I/O:
  ✓ Fine-grained tracing at packet level
  ✓ Packet processing at multiple hosts and different layers.
  Trace metadata propagation is difficult
Time Capsule

Timestamp packet processing at each tracepoint and append the tracing info to the packet *payload*

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**Advantages:**

- Traces embedded in packets go across the boundaries of protection domains
- Timestamps taken at different points have happened-before relation. No need to capture causality
Preserve the last timestamp at a sender to capture causality relationship across machines.
Timestamping at Tracepoints

• Challenges
  ✓ Low overhead
  ✓ Available in separate protection domains
  ✓ Dealing with time drift on multiple hosts

• Solution
  ✓ Para-virtualized clocksouce xen or kvm-clock
  ✓ Function native_read_tscp to read tsc values,
    nanosecond granularity, ~20ns overhead for each reading
  ✓ Set constant_tsc to ensure consistent tsc readings across
difference cores
Timestamping across Machines

• Network transmission time

\[ t_{SC}^b - t_{SC}^a \]

• Transmission time can be negative or inaccurate
  ✓ TSC ticks at different rates on machines \( a \) and \( b \)
  ✓ TSC resets at different times on machines \( a \) and \( b \)
TSC Calibration

**Objective:**
Estimate t2 – t1 using readings of tsc_b and tsc_a

**Steps:**
1) Estimate machine α’s tsc reading tsc’_a at t1 as if both machines reset tsc at the same time
2) Convert tsc’_a to tsc’_b, the equivalent tsc reading on machine b
3) Calculate packet transmission time as tsc_b – tsc’_b

More details in the paper

**Notation:**
- α: time difference when two machines’ tsc was reset
- β: absolute tsc difference
- cpufreq: CPU frequency of a machine
Tracing Payload

- Use `__skb_put` to append trace data to the original payload
- Each timestamp is 8 bytes
- Sampling decision bit determines the sampling rate
- Annotation bit decides which tracepoint(s) to enable
Trace Collection

• Ring buffers in physical NIC driver (Tx) and guest OS network stack (Rx)

• Tracing data is removed from the packet payload and copied to the ring buffers
  ✓ Before packet is copied to user space (Rx)
  ✓ Before packet is transmitted by NIC driver (Tx)

• mmap the ring buffers to /proc file systems in user space

• Periodically dump trace to storage for latency analysis
Evaluation

**Hardware**

- two PowerEdge T420 servers
- two 6-core 1.90GHz Intel Xeon E5-2420 CPUs
- 32GB memory
- Gigabit Ethernet

**Software**

- Hypervisor: Xen 4.5
- Dom 0 and Dom U kernel: Linux 3.18.21
- VM: 1 vCPU + 4GB memory
Time Capsule Overhead

Time Capsule incurs no more than 2% latency increase

Sockperf UDP latency
Per Packet Latency

Packet level latency monitoring:
1. Capture latency fluctuation
2. More responsive to traffic change
3. Capture transient spikes in user-perceived latency

Average latency per second

Latency per packet

Foreground sockperf UDP request
Background netperf interference arrive at the 1.5th second and left at the 6.5th second
Diagnosis with Latency Breakdown

Colocation of latency-sensitive and throughput-intensive workloads in the same VM incurs long and unpredictable latency.

Latency breakdown reveals that packet batching at the backend NIC driver was the culprit.
Taming Long Tail Latency in Xen

Case 1

VM-1
sockperf

Xen

Case 2

VM-1
sockperf

VM-2
loop

Xen

Bugs in Xen’s credit scheduler
Time capsule helps find them!
**Observations:**

1. Predictable latency spike every 250 packets
2. The tail latency close to 30ms
3. Spike always starting with delay in Xen

**Case 2**

- Dom0
- Xen
- DomU

BUG-1: Xen mistakenly boosts the priority of CPU-intensive VMs, which causes long scheduling delays of the I/O-bound VM in Xen

After BUG-1 is Fixed

Tail latency is still not bounded
Additional Xen Bugs

**Observations:**
1. The occurrence and magnitude of the latency spike are unpredictable
2. Spike always starting with delay in Xen

**BUG-2:** Xen does not timely activate I/O VMs that are deactivated due to long idling

**BUG-3:** I/O VMs’ BOOST priority can be prematurely demoted
Future Work

• **Dynamic instrumentation**
  ✓ Extend Time Capsule to dynamically add tracepoints using BPF

• **Automated analysis**
  ✓ use machine learning to extract better information from packet traces

• **Disk I/O**
  ✓ extend TC to disk I/O requests. Challenge is the lack of a commonly shared data structure, such as skb in networking, across layers in virtualized block I/O stacks
Conclusions

• **Motivation**
  Tracing latency in virtualized systems is challenging due to the isolation of protection domains and requirements for low overhead and application transparency

• **Time Capsule**
  An in-band profiler to trace network latency at packet level in virtualized environments

• **Evaluation**
  Time Capsule incurs low overhead, enables fine-grained packet level tracing, and latency breakdown, which helps to detect bugs that cause long tail latency in Xen
Thank you!

Questions?
FAQ

• **Will time capsule affect the user-perceived packet size?**

  No and yes. When packets are received, MTU is no longer a limit for packet size. Time capsule is able to append as much data as needed to the payload and the tracing payload is removed before the packet arrives at the user space. Thus, the users are unaware of the tracing activities. However, time capsule needs to append 8 bytes to the packet to store the last timestamp at the sender side. In rare cases, this will affect the number of packets transmitted. For example, if the original packet size is 2999 bytes (a little less than two MTUs), adding 8 bytes to the original payload will require one more packet to be transmitted.