Efficient and Scalable Virtio (aka ELVIS)

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Why (not) Virtio?

- **Pros**
  - Software Defined Networking
  - File based images
  - Live Migration
  - Fault Tolerance
  - Security
  - ....

- **Cons**
  - Scalability Limitations
  - Performance Degradation
  - Scalability Limitations
  - Performance Degradation
I/O Virtualization Models

- Bare-metal I/O (no VM)
- SR-IOV + ELI
- ELVIS
- Virtio (para-virtual)
- Emulated I/O

Scalability and Performance

Flexibility

Interposable

Non-virtualizable

Non-interposable

Unmodified Guest
How Virtio works today?

- The guest posts I/O requests in ring-queue (shared with the QEMU or vhost) and sends a request notification (PIO)
- QEMU or vhost processes the requests and sends a reply notification (virtual interrupt)
How I/O notifications are sent/received

- CPU context switch (VMExits and VMEntries)
- I/O processing
- Guest execution

- VCPU Thread (Core X)
- I/O notification Guest-to-Host
- PIO
- Forced Exit (via IPI)
- I/O notification Host-to-Guest

- I/O Thread (Core Y)
- Process I/O Request
- Complete I/O Request

- 1 thread per virtual CPU (VCPU)
- 1 or more threads per virtual I/O device

Virtual Interrupt Injection
Is this model scalable with the number of guests, cores and I/O bandwidth?

VCPU and I/O thread-based scheduling for all cores (host Linux scheduler)

Execution Time

Depends on Linux (host) thread scheduler but the scheduler has no information about the I/O activity of the Virtio queues....
Facts and Trends

- Notifications cause exits (context switches) == overhead!
- Current trend is:
  - Towards multi-core systems with an increasing numbers of cores per socket (4->6->8->16->32) and guests per host
  - Faster networks with expectation of lower latency and higher bandwidth (1GbE->10GbE->40GbE->100GbE)
- I/O virtualization is a CPU intensive task, and may require more cycles than the available in a single core

We need a Virtio back-end that considers these facts and trends!
ELVIS (based on vhost): use fine-grained I/O scheduling and dedicate cores to improve scalability and efficiency

- Process queues based on the I/O activity
- Balance between throughput and latency
- No process/thread context switches for I/O
- Exitless communication (next slide)
- Consider if the queue’s owner (VM) is running or not (not yet implemented)

1 vhost thread per I/O core handles requests of many VMs/Virtio devices
ELVIS: remove notifications overhead to further improve efficiency

Traditional Paravirtual I/O

- VCPU Thread (Core X)
- I/O Thread (Core Y)

- Guest-to-Host I/O notification
- Host-to-Guest I/O notification

- Process I/O Request
- Complete I/O Request

Paravirtual I/O

- VCPU Thread (Core X)
- I/O Thread (Core Y)

- Guest-to-Host I/O notification
- Host-to-Guest I/O notification

- Process I/O Request
- Complete I/O Request

Polled I/O

- I/O notification
- Process I/O Request
- Complete I/O Request

Para-virtual posted interrupts (via ELI)
ELI: Exitless Interrupts to simulate Posted Interrupts

- ELI configures the CPU to deliver all interrupts to the guest
- ELI runs the guest using a shadow IDT
- Host interrupts are bounced back to the host in the form of exceptions and re-generated with software interrupts/self IPI
- …without the guest being aware of it

![Diagram showing the setup of ELI interrupt delivery]

- **Guest IDT**
- **Interrupt Handler**
- **Assigned Interrupt**
- **Shadow IDT**
- **VM**
- **ELI Delivery**
- **Physical Interrupt**
- **KVM**

![Diagram of Shadow IDT]

- **Shadow IDT**
- **IDT Entry**
- **P=0**
- **#NP**
- **Handler**
- **IDT Entry**
- **P=1**
- **#NP**
- **IDT Entry**
- **P=0**
- **#GP**

![Diagram of IDT Entry]

- **IDT Entry**
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ELI: Exitless Interrupts - Completion

- Guests write to the LAPIC EOI register

- Old LAPIC interface:
  - KVM traps memory accesses → page granularity

- New LAPIC interface (x2APIC), required for Exitless Completions
  - KVM traps accesses to MSRs → register granularity

ELI gives direct access only to the EOI register
Para-Virtual Posted Interrupts based on ELI

- Posted-Interrupts: new HW feature to inject a virtual interrupt from a core running in root mode to a VM running in a different core (guest mode) without forcing an exit

- Para-Virtual Posted interrupts:
  - Write the virtual interrupt vector to be injected in a descriptor (shared memory between KVM and the guest’s kernel)
  - Send IPI (pre-defined vector) using ELI
  - Guest is modified to handle the IPI and call the corresponding (virtual) interrupt handler
ELVIS: Fine-grained I/O scheduling in a nutshell

- Single vhobot-thread in a dedicated core:
  - Monitors the activity of all queues (number of pending requests, how long the requests are waiting, queue progress…)
  - Decide which queue should be processed and for how long

- Linux scheduler time-slice
- Q2 is stuck
- Min data
- Dedicated I/O Core
- Check queues’ activity
- Max data
- Q2 is Stuck but not passed min

Q1: throughput intensive  Q2: latency sensitive  Q3: throughput intensive
ELVIS: Placement of threads, memory and interrupts

- Dedicate 1 I/O core per CPU socket
  - Cores per socket continue to increase year by year
  - More cores are required to virtualize more bandwidth at lower latencies (network links continue to be improved)
  - NUMA awareness: shared LLC cache and memory controller, DDIO technology

- Deliver interrupts to the “corresponding” I/O core
  - Interrupts are processed by I/O cores and do not disturb the running the guests
  - Improve locality
  - Multi-queue, Multi-port and SR-IOV adapters can dedicate interrupts per queue/port/virtual function
From Research to Practice: Status, Work in Progress and Future Work

- Patches published in github (based on Kernel 3.9)

- Work in progress by Eyal Moscovici <eyalmo@il.ibm.com>
  - Control mechanism (sysfs interface) to:
    - allocate or de-allocate vhost threads on the fly
    - migrate a Virtio device/queue to a different vhost thread on the fly
  - Policy framework to monitor the system and orchestrate the control mechanism

- Get support to upstream the following features:
  1. Shared vhost-thread: same thread handles many virtio devices – default 1 thread per virtio device as it is today
  2. Control mechanism (sysfs): allocate/de-allocate vhost-threads and assign queues to vhost-threads
  3. Vhost statistics (sysfs): expose virtio queues and vhost-thread progress/load
  4. Polling optimization: poll queues to remove PIO exits (guest-to-host notifications)
  5. Policy mechanism: framework and rules to orchestrate the system (Python ?)
  6. Porting to PowerKVM
Performance Evaluation

- Implementation
  - Based on KVM (Linux Kernel 3.1 / QEMU 0.14)
  - With VHOST, in-kernel paravirtual I/O framework
  - Use ELI patches to implement para-virtual posted-interrupts and to improve hardware-assisted non-interposable I/O (SR-IOV)

- Experimental Setup
  - IBM System x3550 M4, dual socket 8 cores per socket Intel Xeon E2660 2.2GHz (SandyBridge)
  - Dual port 10GbE Intel x520 SRIOV NIC
  - 2 identical servers: one used to host the VMs and the other used to generate load on bare-metal
Methodology

- Repeated experiments using 1 to 14 UP VMs
  - 1x10GbE when running up-to 7 VMs
  - 2x10GbE when running more than 7 VMs

- Compared ELVIS against 3 other configurations

- **No interposition**
  - Each VM runs on a dedicated core and has a SR-IOV VF assigned using ELI
  - The closer ELVIS is to this configuration, the smaller the overhead is (used to evaluate ELVIS efficiency)
Methodology (cont.)

- \(N=\text{number of VMs (1 to 14)}\)
- Used \(N+1\) cores \((N \leq 7)\) or \(N+2\) cores \((N>7)\)
  - This is the resource overhead for I/O interposition

- **ELVIS**
  - 1 dedicated core per VCPU (VM)
  - 1 core \((N \leq 7)\) or \((N>7)\) 2 cores dedicated for I/O

- **Baseline**
  - \(N+1\) cores \((N \leq 7)\) or \(N+2\) cores \((N>7)\) to run VCPU and I/O threads (no thread affinity)

- **Baseline+Affinity**
  - Baseline but dedicate 1 core per VCPU and pin I/O threads to dedicated I/O cores
Netperf – TCP Stream 64Bytes (throughput intensive)

1x10Gb port
**ELVIS**: 1 core dedicated for I/O and 1 dedicated core per VM (N+1 total)
**Baseline**: N+1 cores (to handle I/O and to run the VMs)
**No Interposition**: N cores to run the VMs

2x10Gb port
**ELVIS**: 2 cores dedicated for I/O and 1 dedicated core per VM (N+2 total)
**Baseline**: N+2 cores (to handle I/O and to run the VMs)
**No Interposition**: N cores to run the VMs

- Scaled perfectly
- 1 core managed to handle I/O for 7 VMs (cores)
- Maximum throughput
- Coalesced more interrupts than the SR-IOV device (4K-11K vs. 30K ints/sec)
Netperf – UDP Request Response (latency sensitive)

- Latency slightly increased with more VMs
- Better than No Interposition in some cases because enabling SR-IOV in the NIC increases latency by 22% (ELVIS disables SR-IOV)
Memcached - 90% get, 10% set, 32 concurrent requests per VM
1KB value size, 64B key size

- I/O core saturated after 3 VMs
- ELVIS was up to 30% slower than No interposition when the I/O core was not saturated, but was always 30%-115% better than Baseline
Filebench – block I/O interposition based on host RAM disk
4x4KB random writes, 4x4KB random reads per VM

- Latency remains constant
- Throughput increases linearly

Added 1 core
Filebench (*) - 4 threads performing 8KB random reads per VM using fusion-io (PCIe flash) as a block device for the VMs

(*) Evaluation performed by Razya Ladelsky <razyal@il.ibm.com> using a different machine setup, Kernel 3.9, QEMU 1.3, and vhost-block back-end shared by Asias He <asias@redhat.com>

Number of cores used = number of VMs + 1
Conclusions and Future Work

- Current trend towards multi-core systems, towards faster networks and block devices makes Virtio inefficient and not scalable

- ELVIS presents a new efficient and scalable model based on vhost

- Future Work
  - Mechanism to dynamically allocate or release I/O cores and map Virtio queues to I/O cores
  - Policy to monitor the system load, decide how many I/O cores are required and map queues to I/O cores
Questions ?