Securing Self-Virtualizing Ethernet Devices

Igor Smolyar, Muli Ben-Yehuda, Dan Tsafrir

In a nutshell

- We show an attack where an untrusted virtual machine completely controls the network bandwidth of other, unrelated virtual machines
- This attack exploits a vulnerability in self-virtualizing Ethernet NICs
- To defend against the attack, you have to either:
  - Modify device hardware/firmware, or
  - Give up on flow control functionality and lose performance, or
  - Trust your virtual machines
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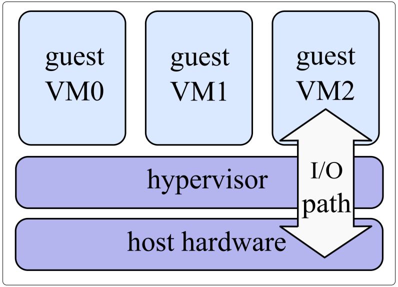
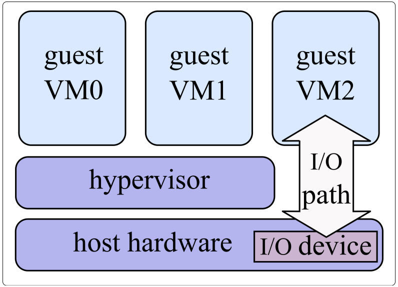
Types of I/O Virtualization



Emulation & Para-virtualization



Direct I/O Device Assignment

Direct Device Assignment

- **Great performance** minimizes the number of I/O-related world switches between the guest and the host
- **Problem: not scalable** ~5-10 I/O devices per host, **but** 50-100 virtual machines per host
- **Solution: self-virtualizing devices** PCI-SIG proposed the Single Root I/O Virtualization (**SRIOV**) standard for scalable device assignment
  - PCI device presents itself as multiple virtual interfaces
  - SRIOV spec supports up to 64K virtual devices
  - Intel XL710 40GbE NIC implements 128 virtual interfaces

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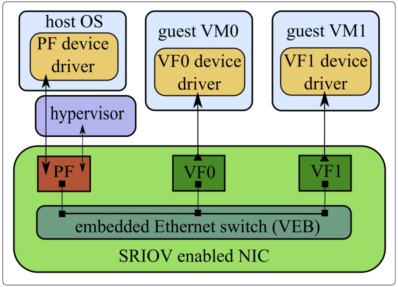
Single Root I/O Virtualization (SRIOV)

Each SRIOV capable device consists of at least one Physical Function (PF) and multiple virtual partitions called Virtual Functions (VF)

- **PF** is a standard PCIe function with full configuration space. Can control entire PCI device and perform I/O operations
- **VF** is a "lightweight" PCI function that implements only only a subset of standard PCI functionality, mostly performs I/O



SRIOV NIC in a virtualized environment

Single Root I/O Virtualization (SRIOV)

- **HPC** with SRIOV it is possible to virtualize HPC setups. Without SRIOV, many use cases in cloud computing, HPC and enterprise data centers would be infeasible
- **Cloud Service Providers** such as Amazon Elastic Compute Cloud (EC2) use SRIOV as the underlying technology in EC2 HPC services
- **Data Centers** Oracle Exalogic Elastic Cloud uses SRIOV technology to share the internal network

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Ethernet Flow Control

- **Traditional Ethernet is lossy** with no guarantee of delivery of Ethernet frames
  - Most data frame drops happen when the receiver's buffers are full and has no memory available to store incoming data frames
  - Assumes that reliability provided by upper-level protocols (e.g. TCP) or applications
- **Ethernet Flow Control (FC)** proposed to create a lossless data link medium
- **Priority Flow Control (PFC)** extends FC for data centers, part of Data Center Bridging (DCB) or Converged Enhanced Ethernet (CEE)

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1. The sender (e.g. Ethernet switch) transmits data faster than the receiver can process
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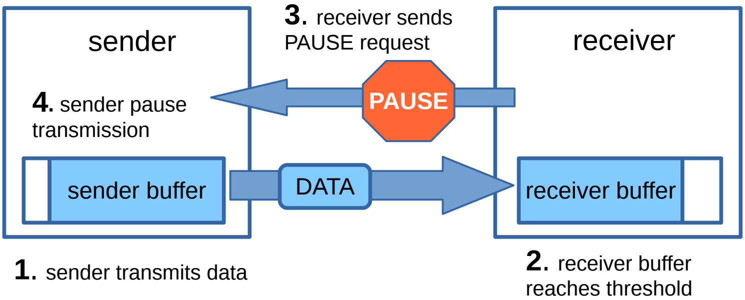

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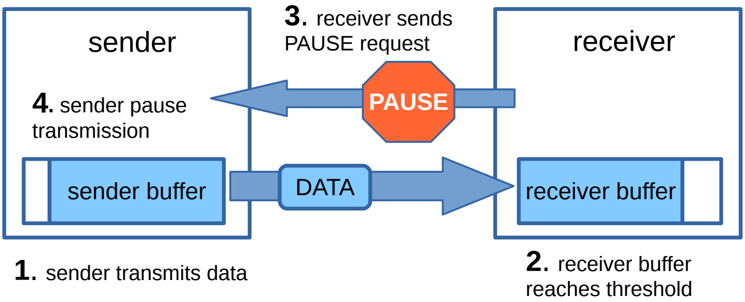

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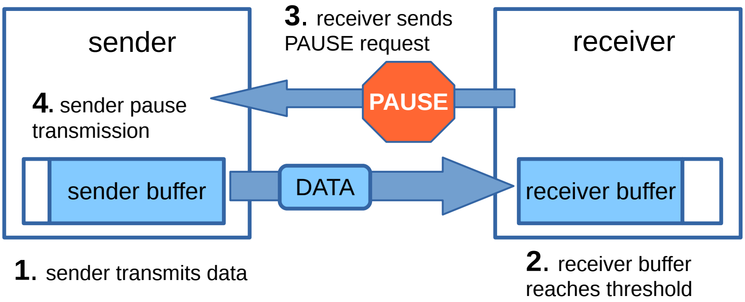

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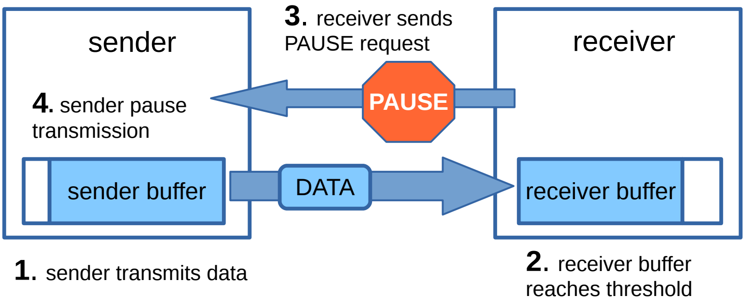

Ethernet Flow Control

link speed, Gbps	single frame pause time, ms	frame rate required to stop transmission, frames/second
1	33.6	30
10	3.36	299
40	0.85	1193

Table : Pause frame rate for stopping traffic completely

Attacking VMs via Flow Control

- **Flow Control** works on link-level
- **Link is shared** between VMs; all VMs with direct access to the VFs of the same PF share the same physical link to the edge switch
- **Each FC Pause Frame** halts traffic on the *entire* link
- **All VFs** associated with this PF are affected

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- The malicious VM sends a pause frame
- **All traffic on the shared link pauses**
- And then continues. . .
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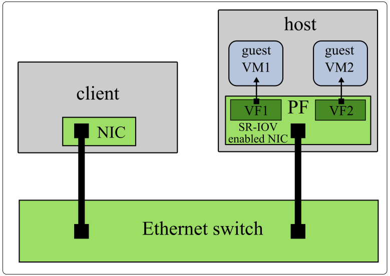
Attack Evaluation—Setup

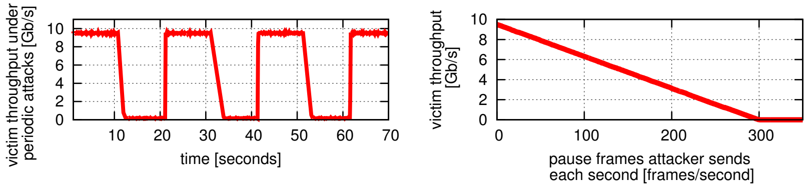
Our testbed consists of two identical servers: one acting as client and the other as the host with SRIOV capable NIC

- On host VF1 assigned to guest VM1 and VF2 to guest VM2
- traffic generated between VM1 and the client using `iperf` and `netperf`
- VM2 is the attacking VM1 sending generated PAUSE frames with `tcpreplay`

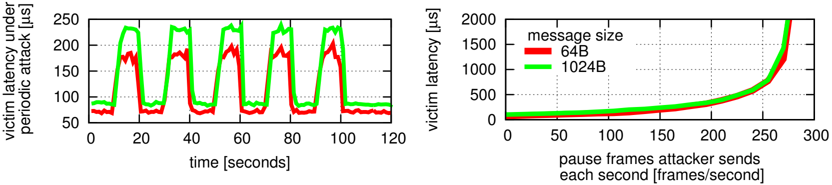


Setup scheme

Attack Results using Intel 10GbE NIC



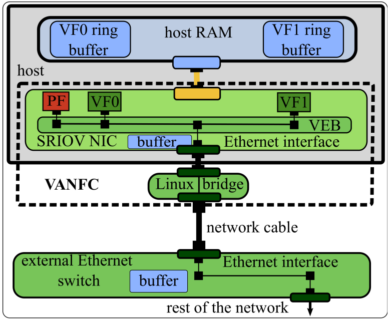
Pause frame attack: victim throughput in 10GbE environment



Pause frame attack: victim latency in 10GbE environment

The Virtualization-Aware Network Flow Controller design

- **Filter** outbound traffic transmitted by a VF
- **Internal switch** replicates Ethernet switch
- **All valid** pause frames are generated by the NIC's hardware and have the PF's source MAC address
- **All malicious** pause frames are sent with source address of a VF



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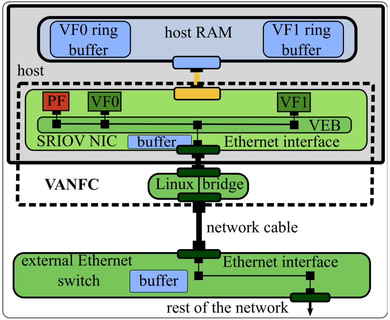

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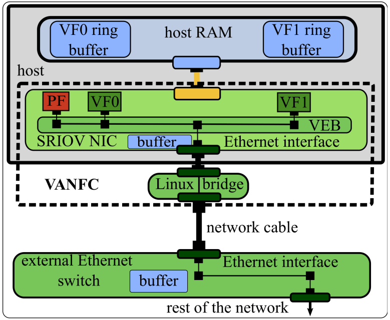

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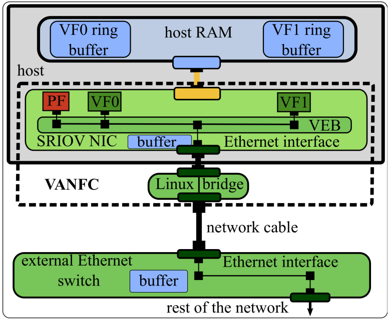

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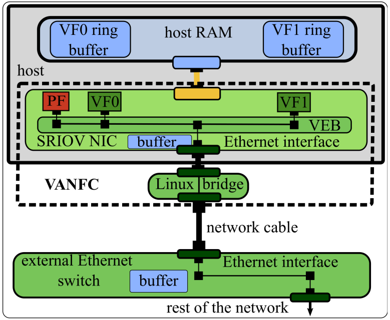

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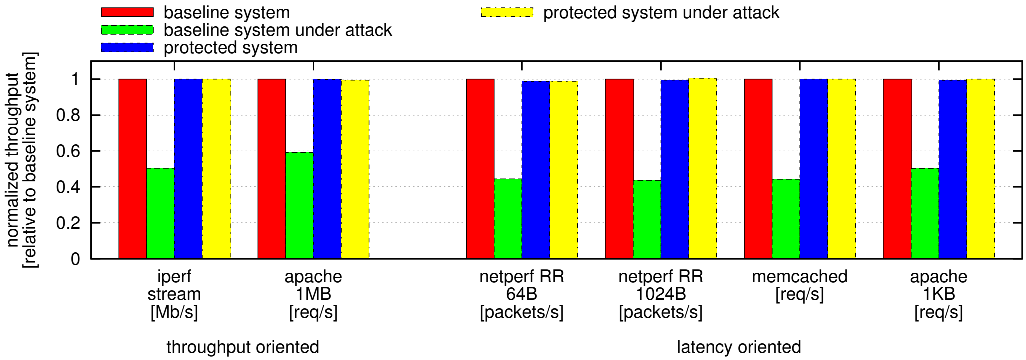
Evaluating VANFC

VANFC completely blocks VM2's attack and introduces no performance penalty



VANFC performance evaluation results

Conclusions

- SRIOV, as currently deployed on current Ethernet networks, is incompatible with flow control
- Removing host from the I/O path requires adding functionality to the hardware
- VANFC 100% effective in securing SRIOV against this flaw while imposing no overhead on throughput or latency
- Future work:
  - Extend to SRIOV InfiniBand and Fiber Channel, NVMe SSD and GPGU
  - Develop VF co-residency detection techniques
  - Use the hypervisor to solve the problem of VM ring buffer exhaustion

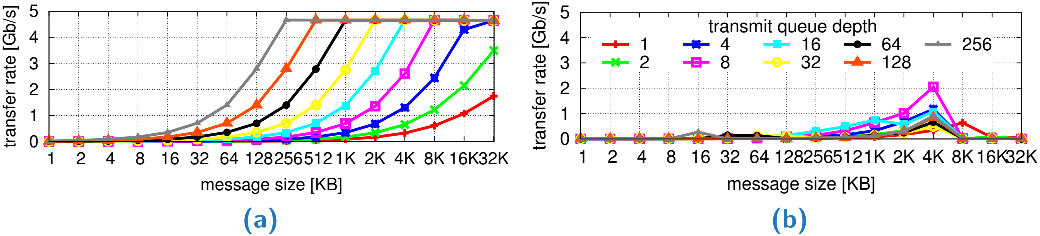
Thank You

Questions?

Can SRIOV be "secured" by disabling FC?

- TCP has its own flow control; however
  - relying on TCP alone for flow control leads to increased resource utilization
  - higher CPU utilization results in higher charges
  - TCP `incast` problem requires flow control
- Remote DMA over Converged Ethernet (RoCE) significantly reduces CPU utilization when compared with TCP
  - Kissel et al. show that on 40 GbE link, sender CPU utilization reduced from 100% using TCP to 2% using RoCE
  - Kissel et al. also show that the same problem is relevant not only to RoCE but can be generalized to TCP as well

Performance of a single RoCE flow in the system with two competing RoCE flows[1]



Graph (a) shows performance with enabled flow control; graph (b) shows performance with disabled flow control.

[1] Taken from Kissel et al. with the authors' explicit permission