SG-IOV: Socket-Granular I/O Virtualization for SmartNIC-Based Container Networks

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ASPLOS 2026

Container Networks Underpin Modern Cloud

Container Networks Underpin Modern Cloud

Container Service

Container Networks Underpin Modern Cloud

Container Service

Google
GKE

AWS
Fargate

Azure
AKS

Container Network (CNI)

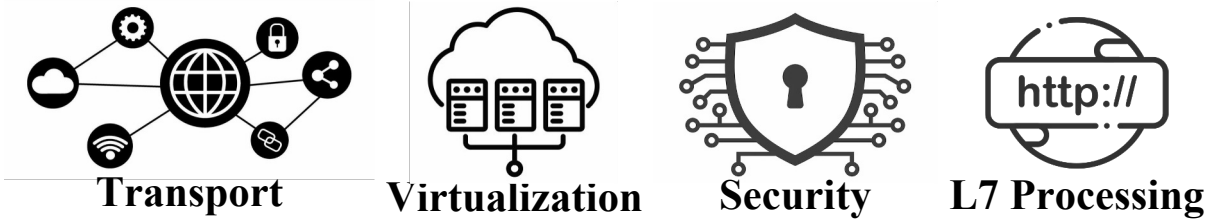
cilium

Container Networks Underpin Modern Cloud

Container Service

Container Network (CNI)

Rich Functionalities



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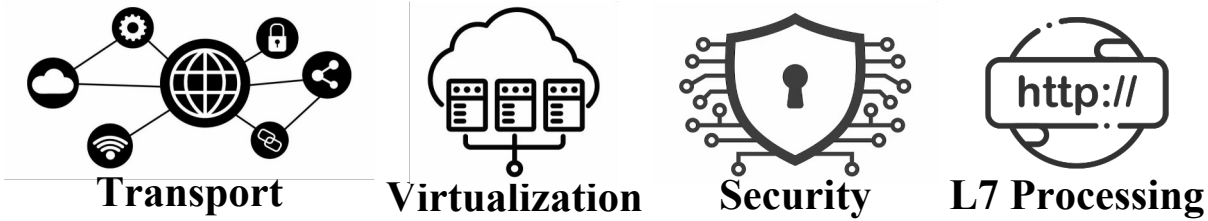

More and more features—but what about the infrastructure cost?

Design Space (1/3): How to Build Efficient CNI?

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Build Container Networks

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- Choice#1: Software Solutions
  - *e.g.*, Cilium CNI

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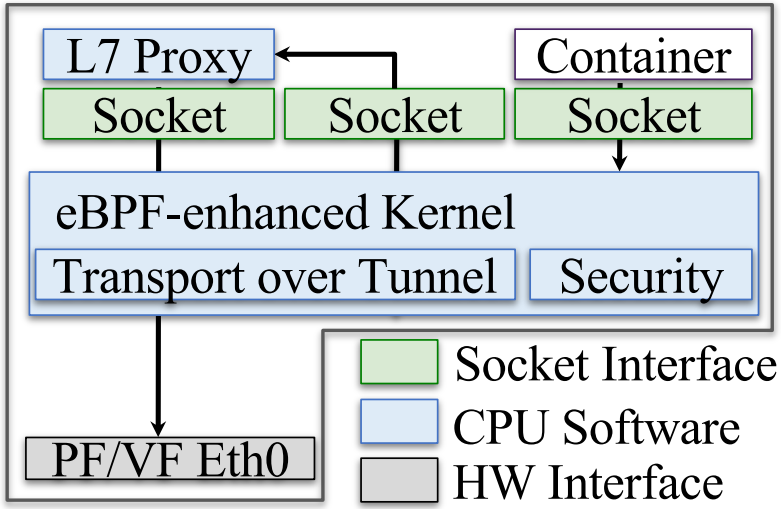

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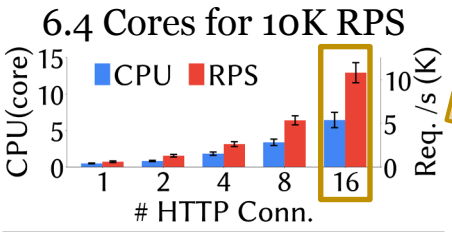

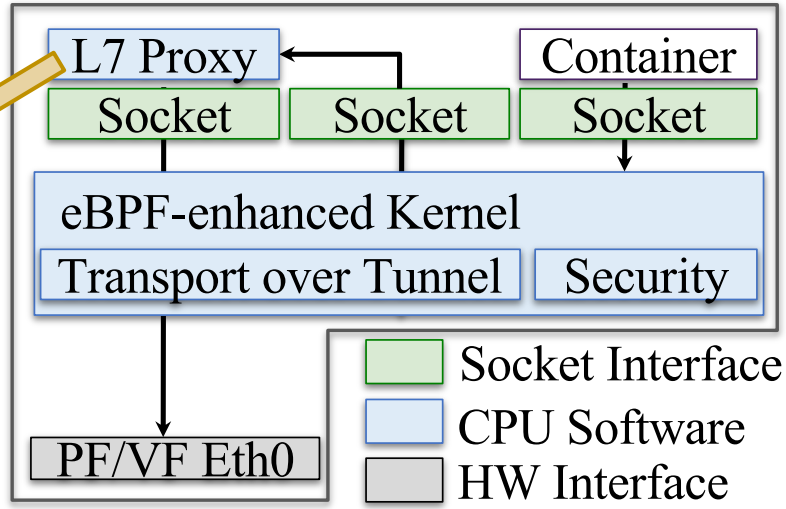

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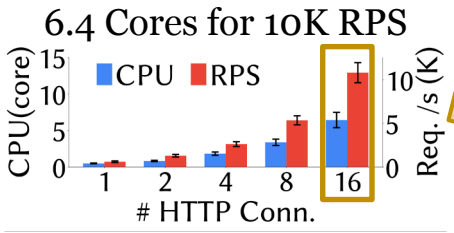

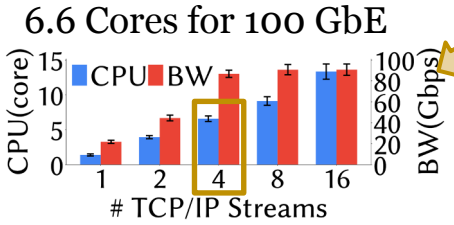

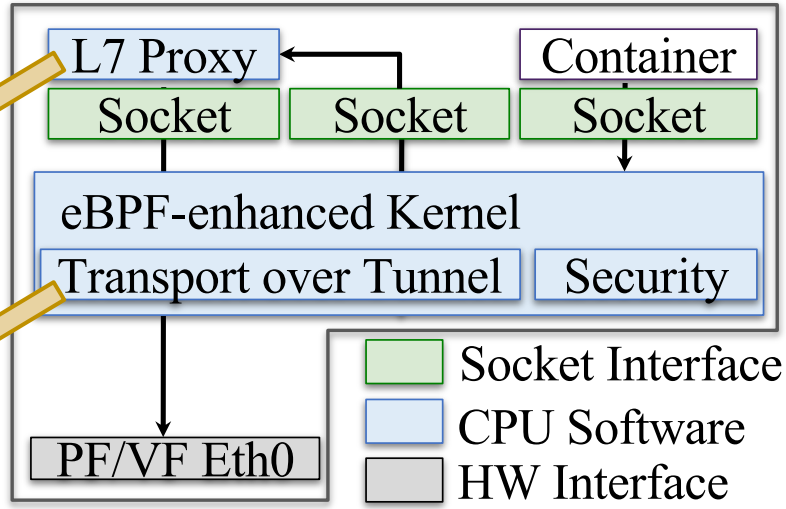

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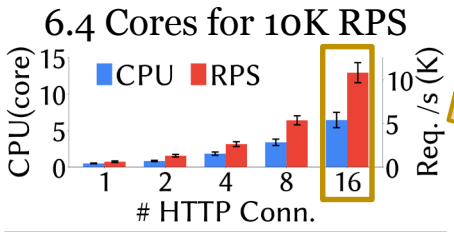

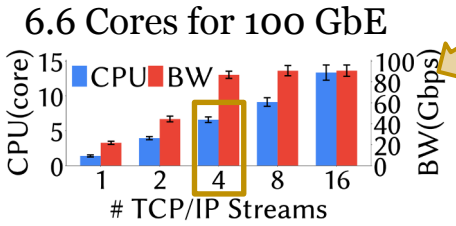

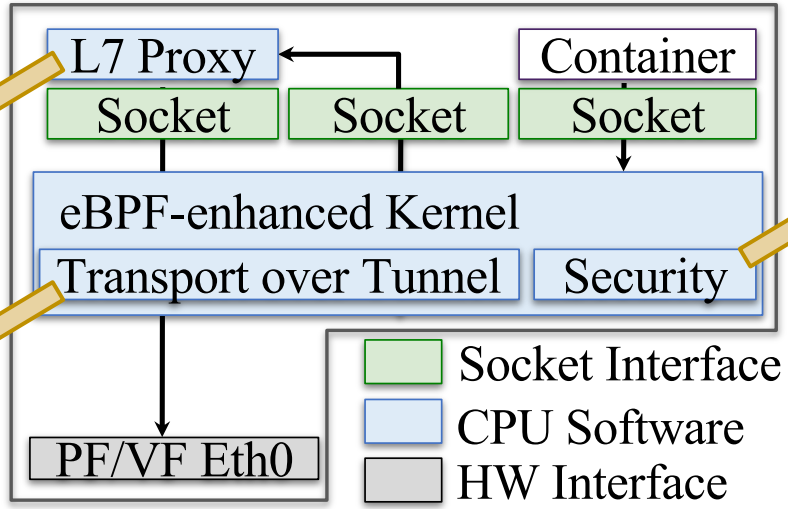

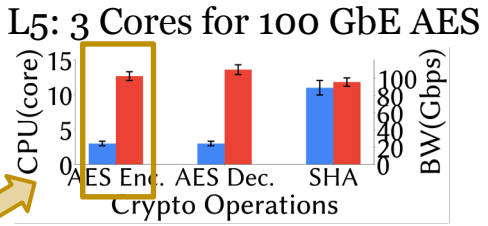

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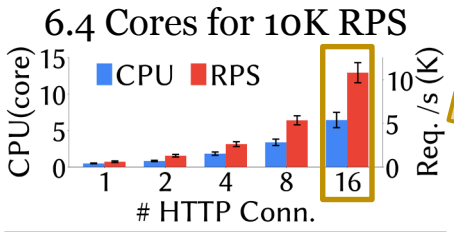

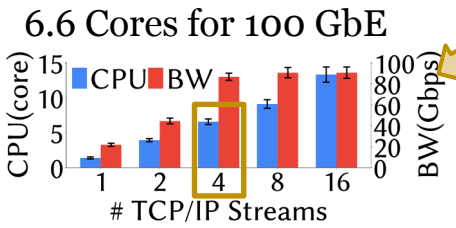

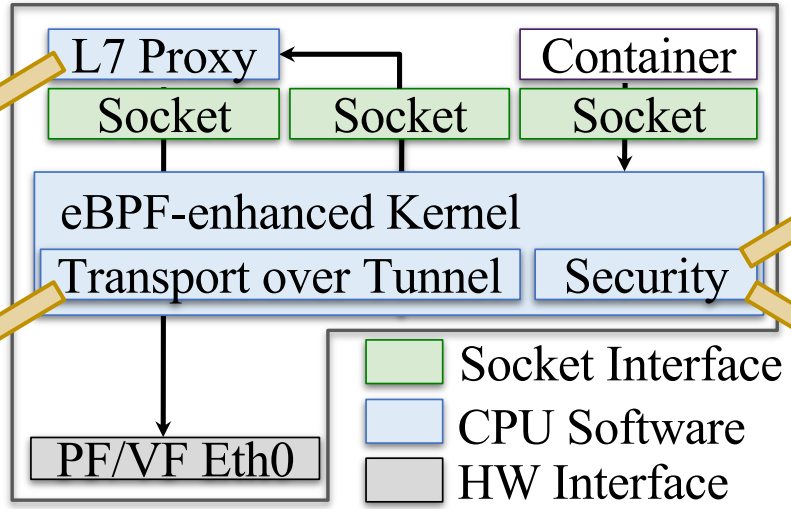

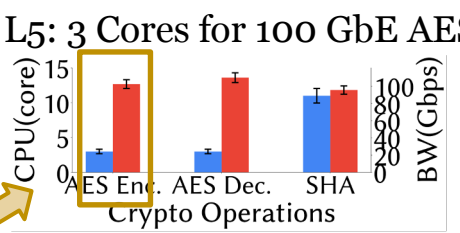

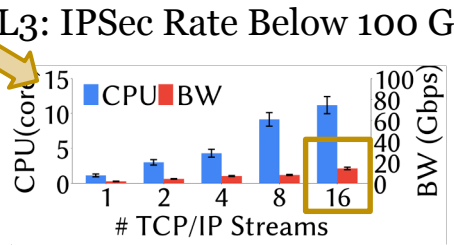

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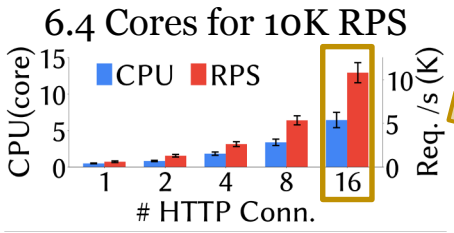

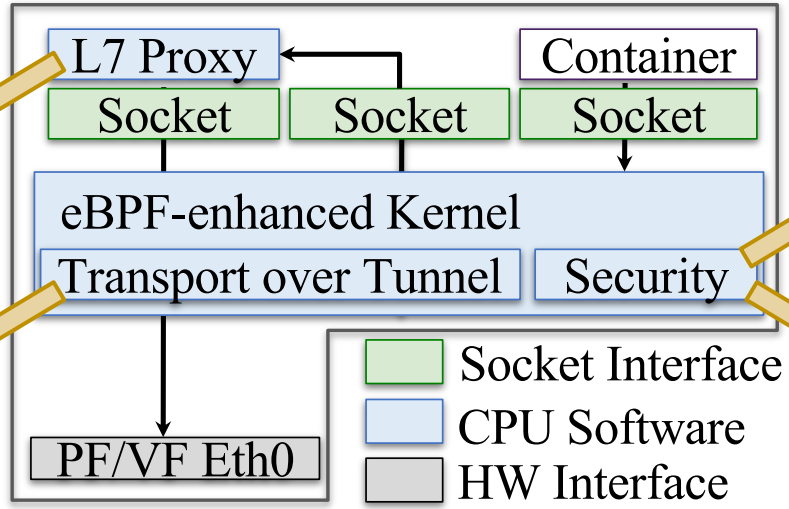

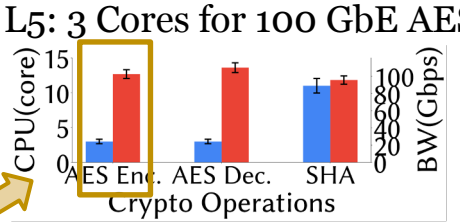

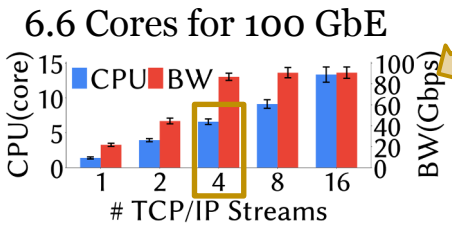

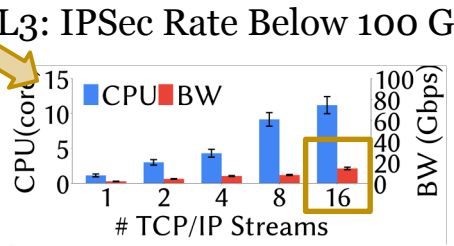

Software CNI: high CPU tax, low efficiency

Design Space (2/3): How to Build Efficient CNI?

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Software Solutions

Design Space (2/3): How to Build Efficient CNI?

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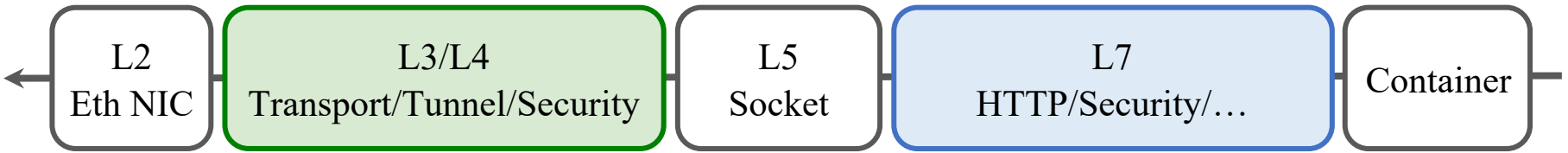
- Choice#2: Which Layer to Offload?

Build Container Networks

Software Solutions | **Hardware Offloading**



Design Space (2/3): How to Build Efficient CNI?

- Choice#2: Which Layer to Offload?
  - Key Boundary: L5 Socket

Build Container Networks

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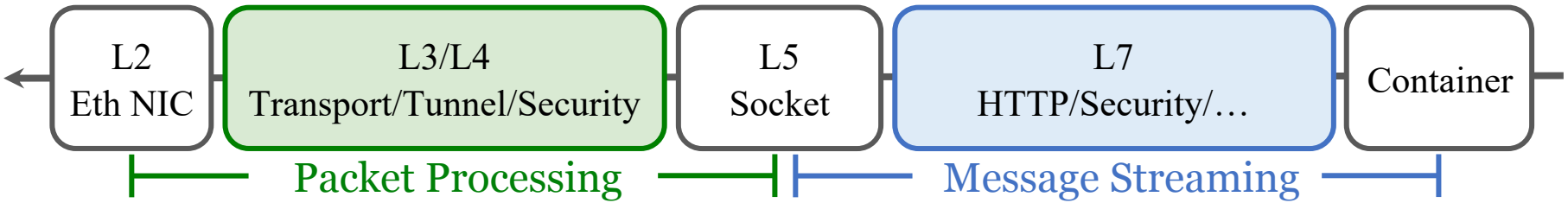

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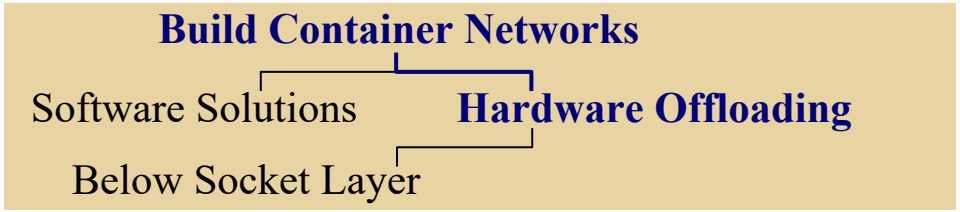

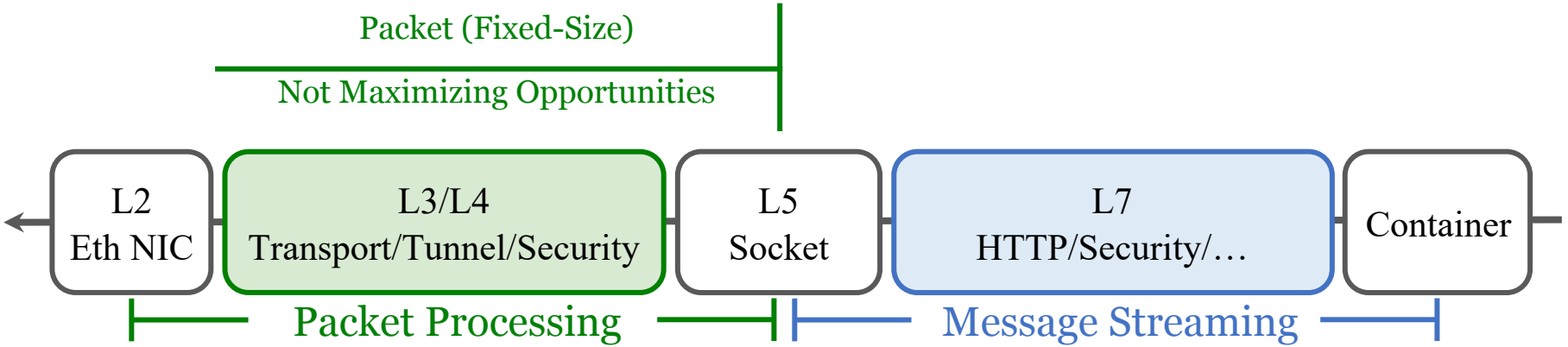

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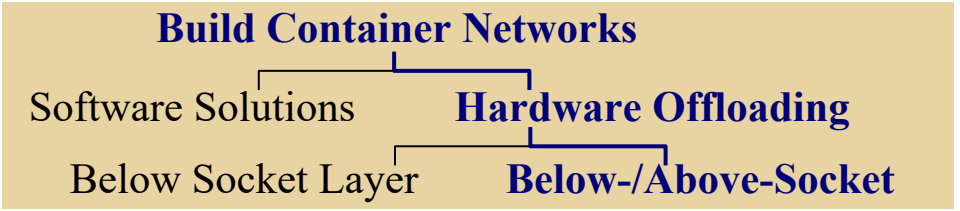

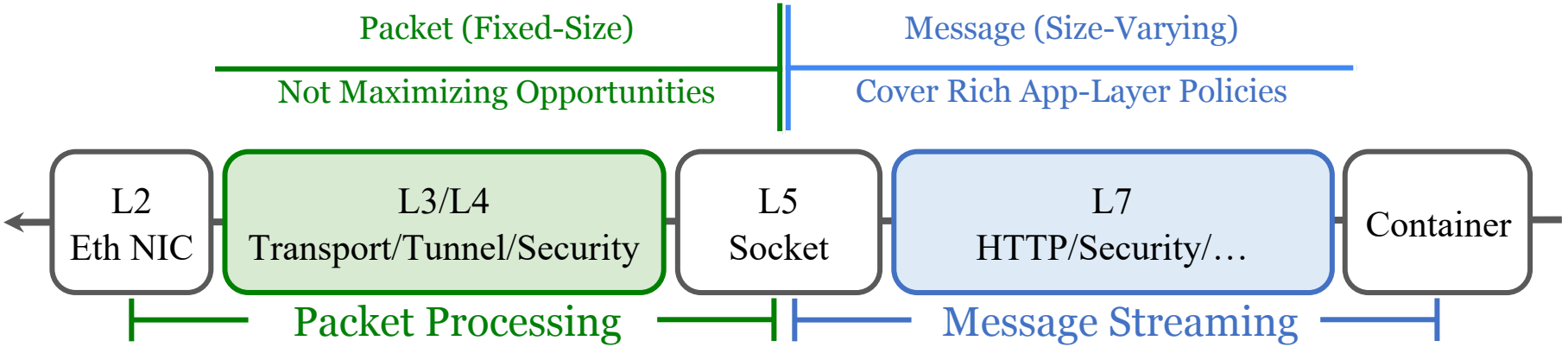

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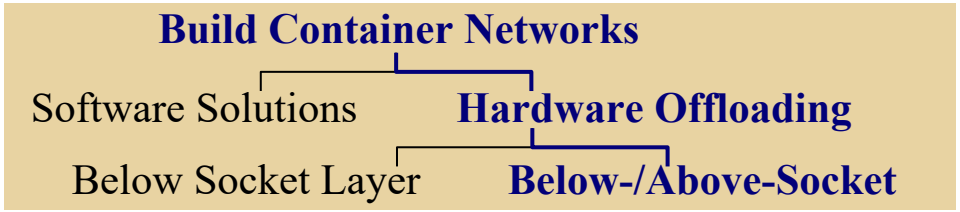
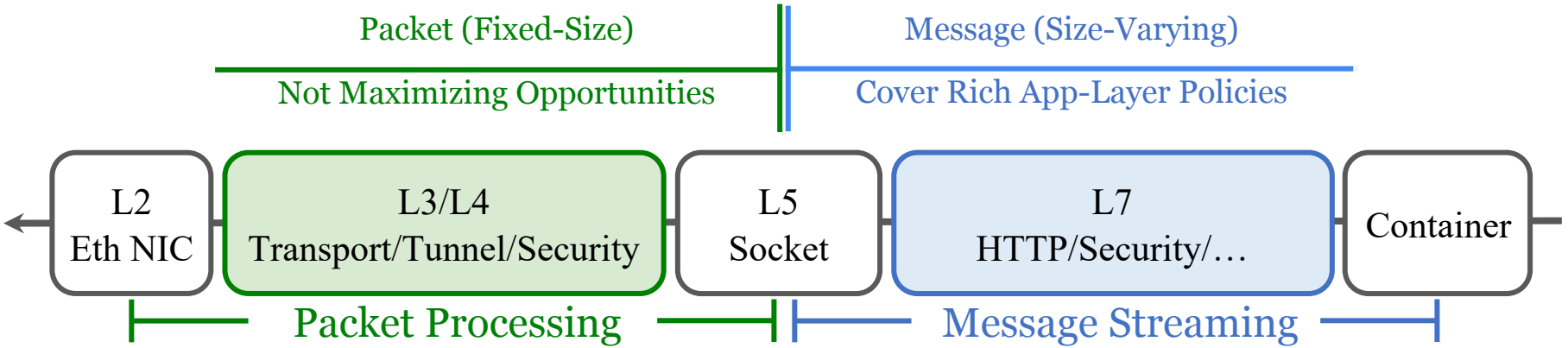
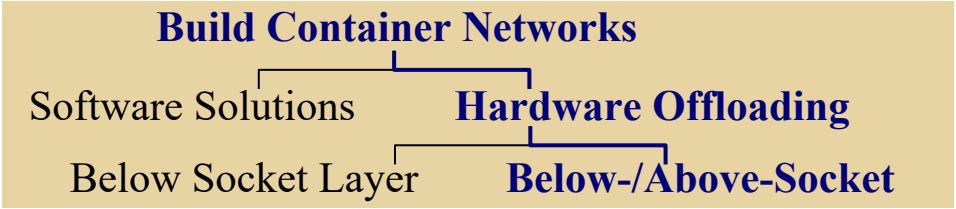




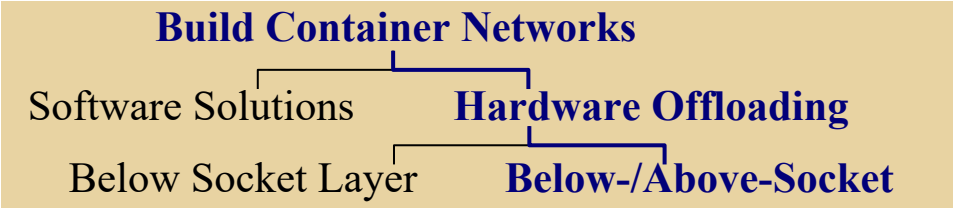
L5+ offload: more opportunities, but rich policies require streaming messages

Design Space (3/3): How to Build Efficient CNI?



Design Space (3/3): How to Build Efficient CNI?

- Choice#3: How to Build an IOV Interface for L5+ Offloading?



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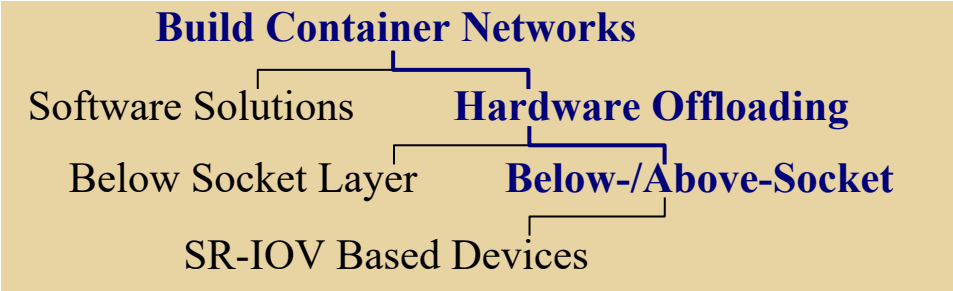
  - Limitations of the *de facto* SR-IOV



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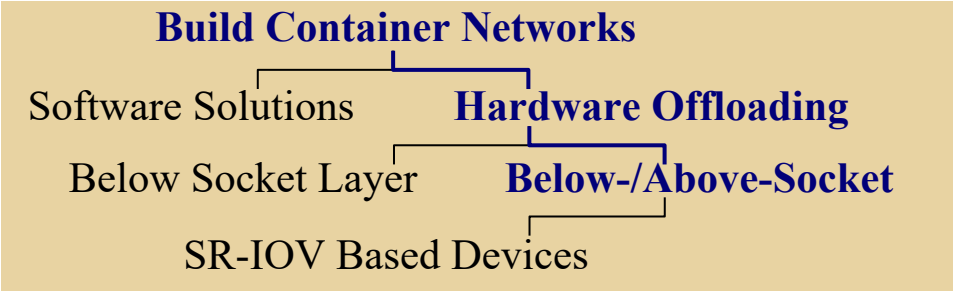

	SR-IOV	Container Needs
Scalability Gap	Low Device Count (100s VF/PF)	High Container Density (1k+ Containers/Node)

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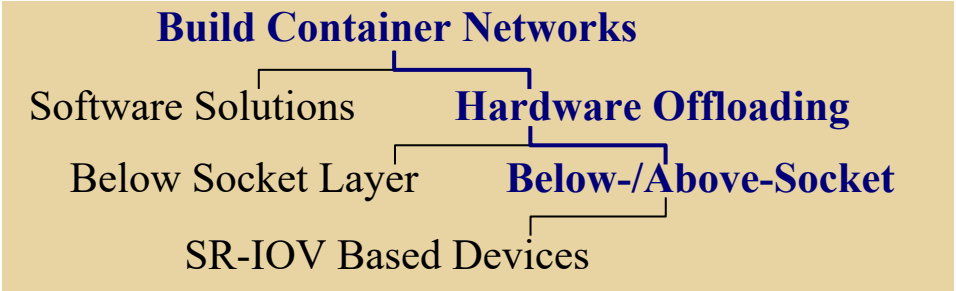

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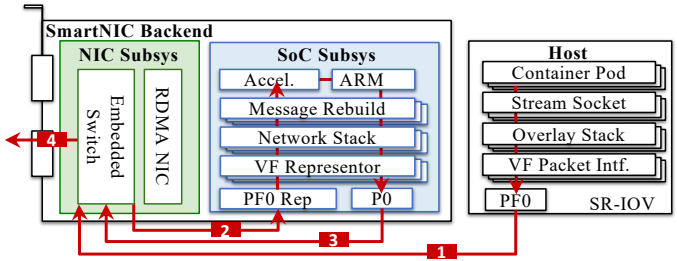

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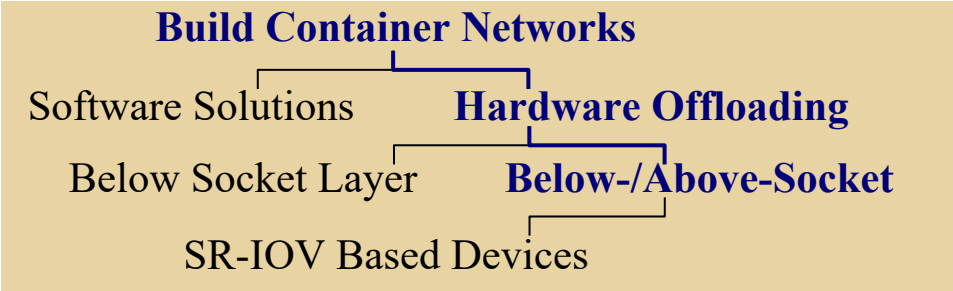

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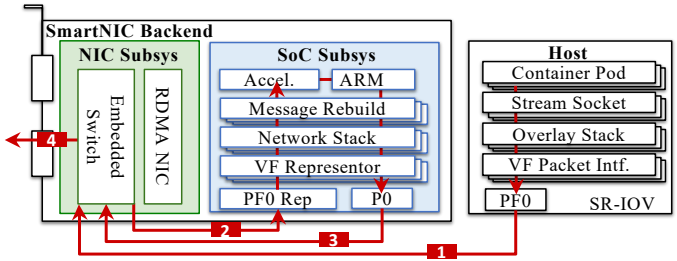

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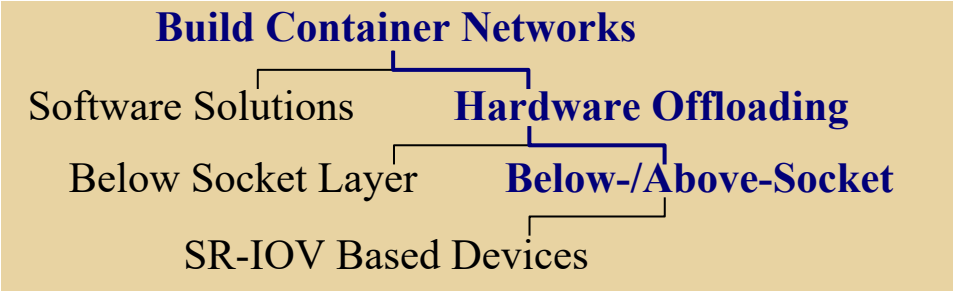

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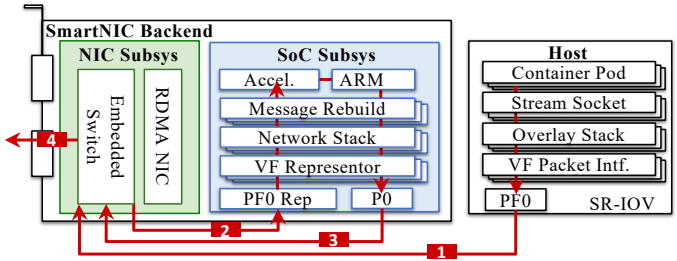

Existing SR-IOV is misaligned with container needs

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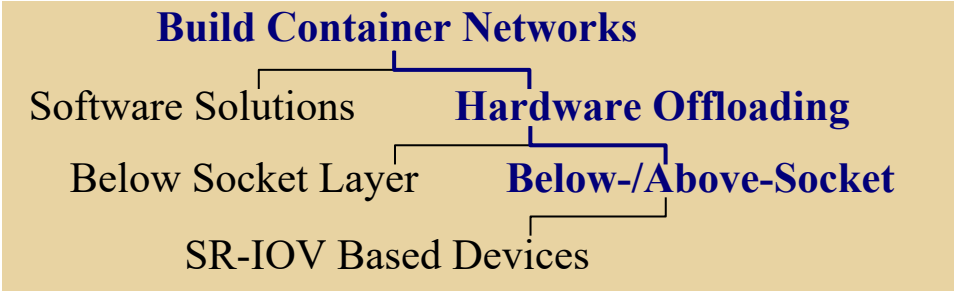

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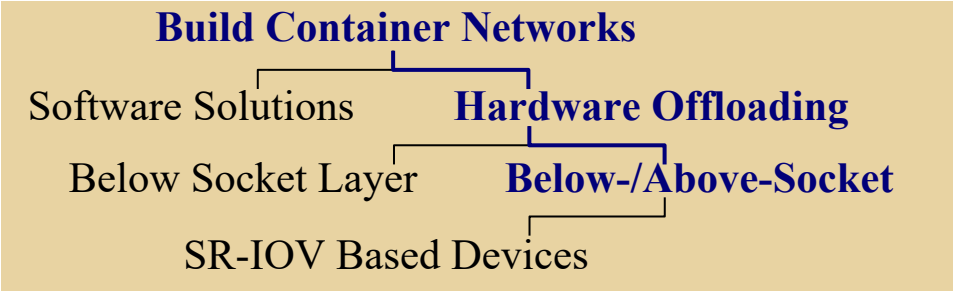
- Let's Rethink Hardware IOV



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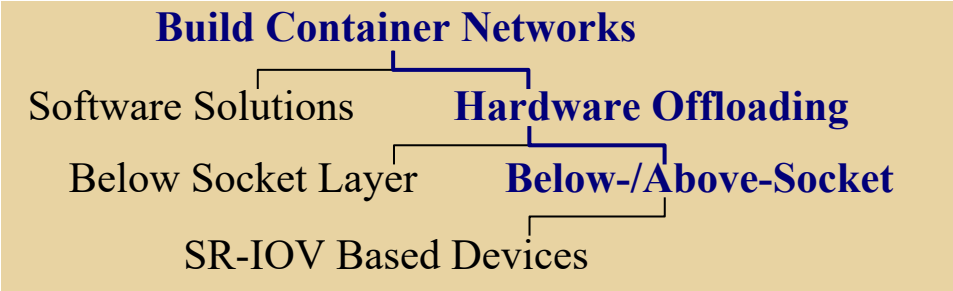
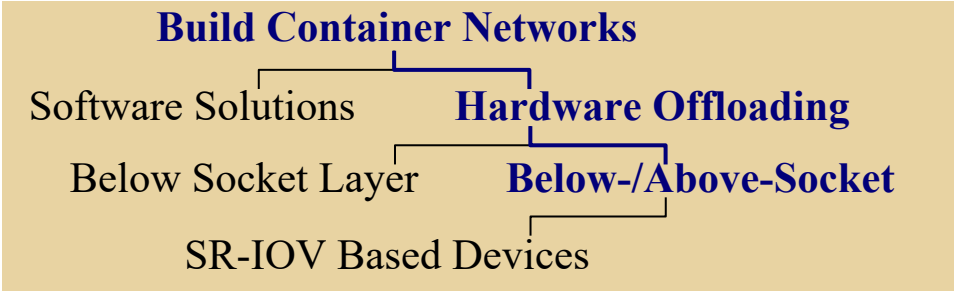


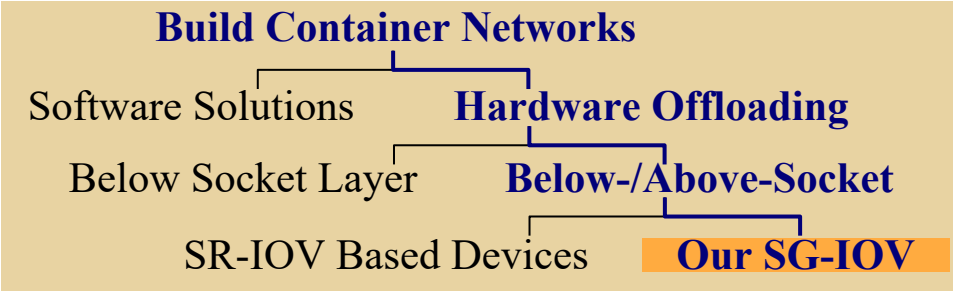
Can Hardware I/O Virtualization Operate at L5 Socket Granularity?

Ours: Socket-Granular I/O Virtualization



Ours: Socket-Granular I/O Virtualization

- SG-IOV: A New IOV Mechanism
  - Socket-Level Devices
  - Message-Stream Abstraction
  - Granular Virtualization



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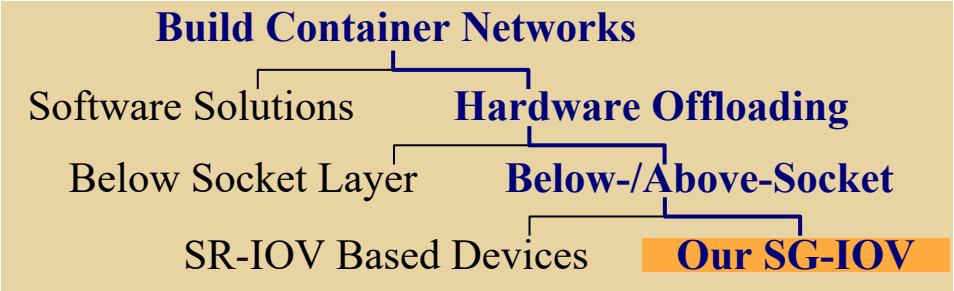

	SW-CNI	SR-IOV	Sub-Func.	TOE	**SG-IOV**
HW Offload	❌	✅	✅	✅	✅
Scalability	✅	❌	✅	✅	✅
Flexibility	✅	❌	❌	❌	✅
Granular HW Virtualization	❌	❌	❌	❌	✅

**SW-CNI: Software CNI; Sub-Func: NVIDIA Scalable Functions; TOE: TCP Offload Engine*

Enabler: SmartNIC Offers Diverse Processing Units

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- End Host w/ SmartNIC Enclosing Heterogeneous Units

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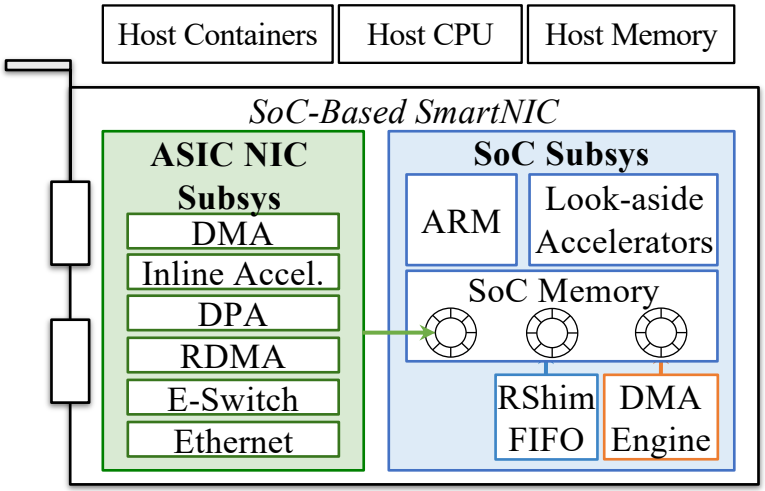
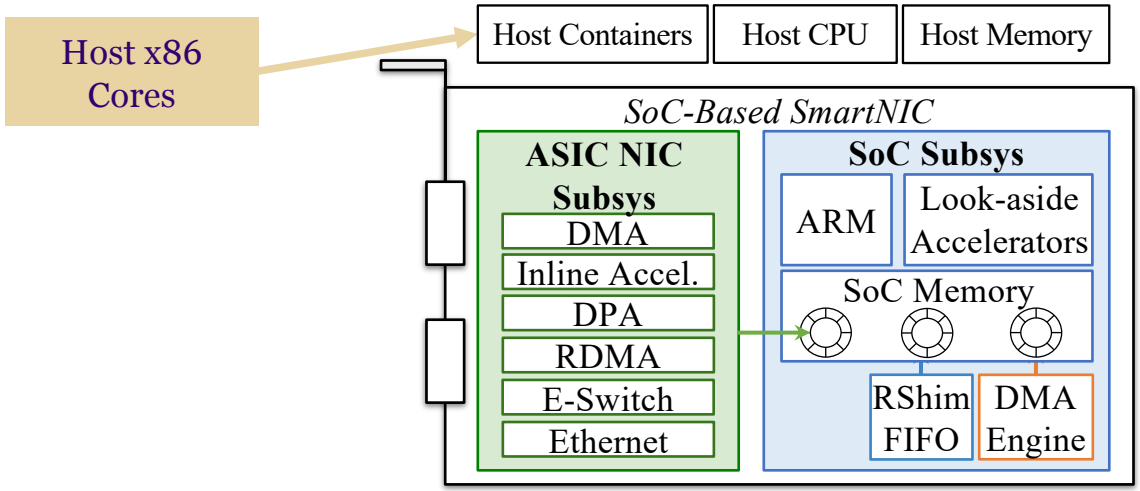


[NVIDIA BlueField-3 SmartNIC as an Example]

Enabler: SmartNIC Offers Diverse Processing Units

- End Host w/ SmartNIC Enclosing Heterogeneous Units



[NVIDIA BlueField-3 SmartNIC as an Example]

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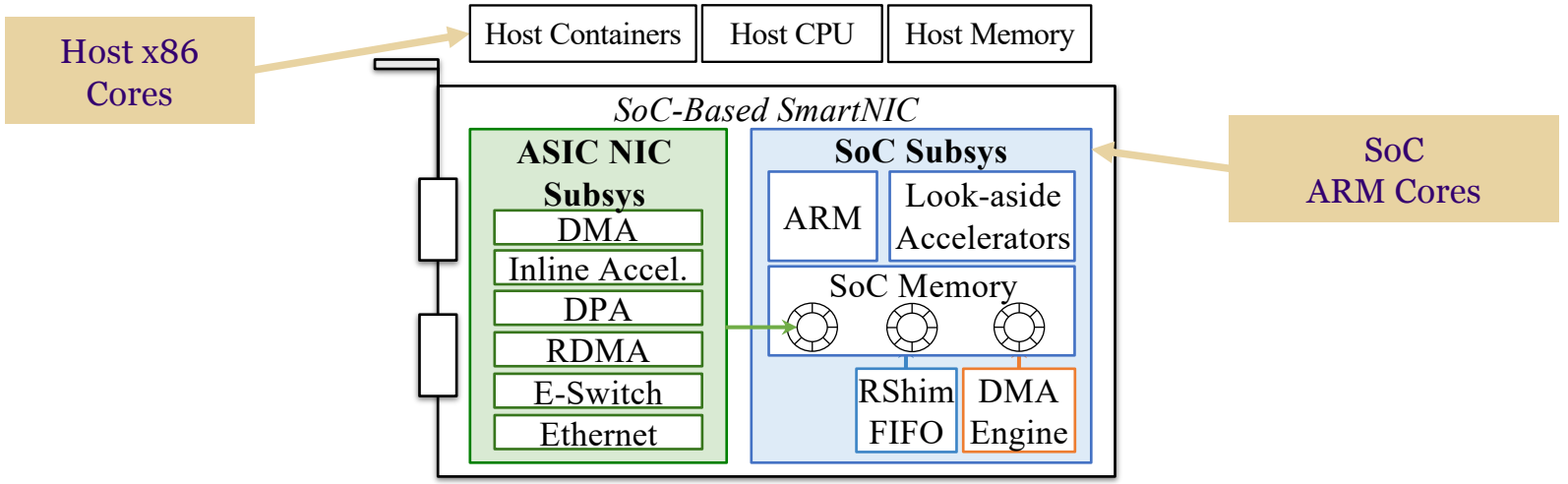

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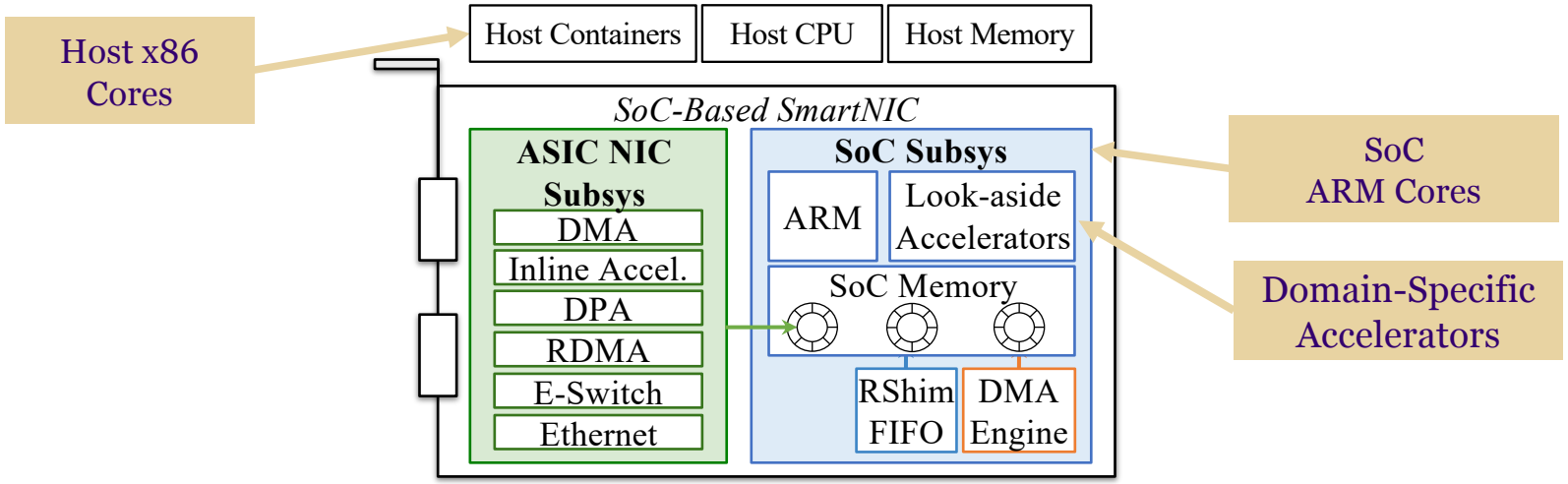

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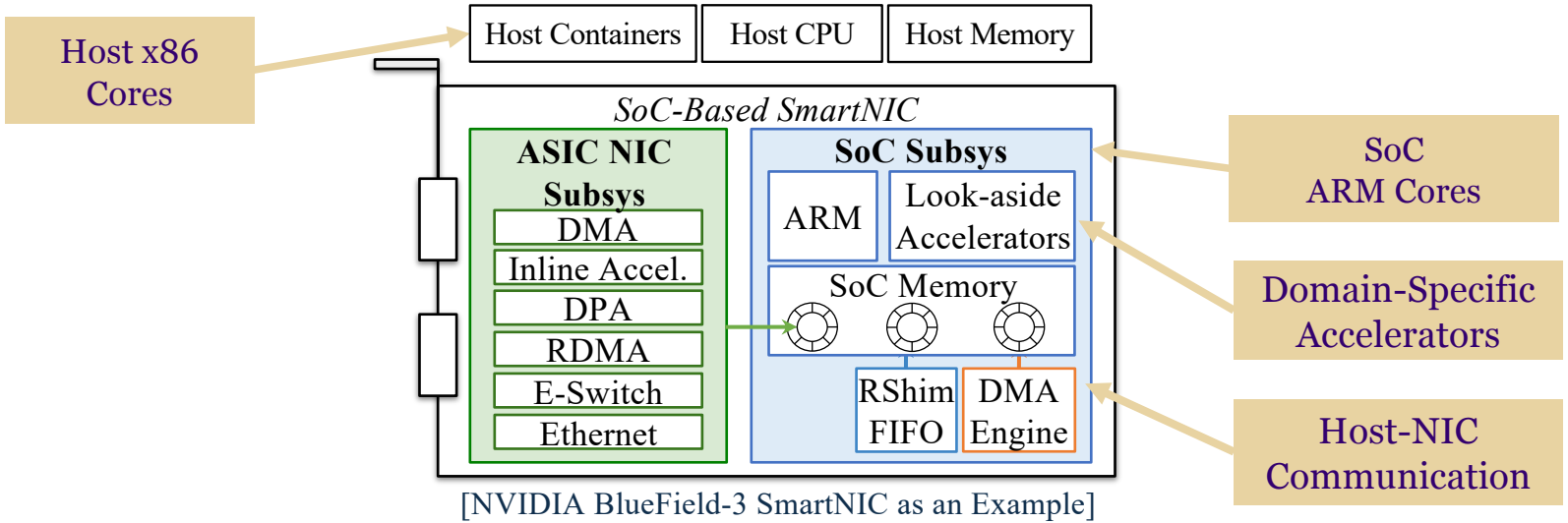

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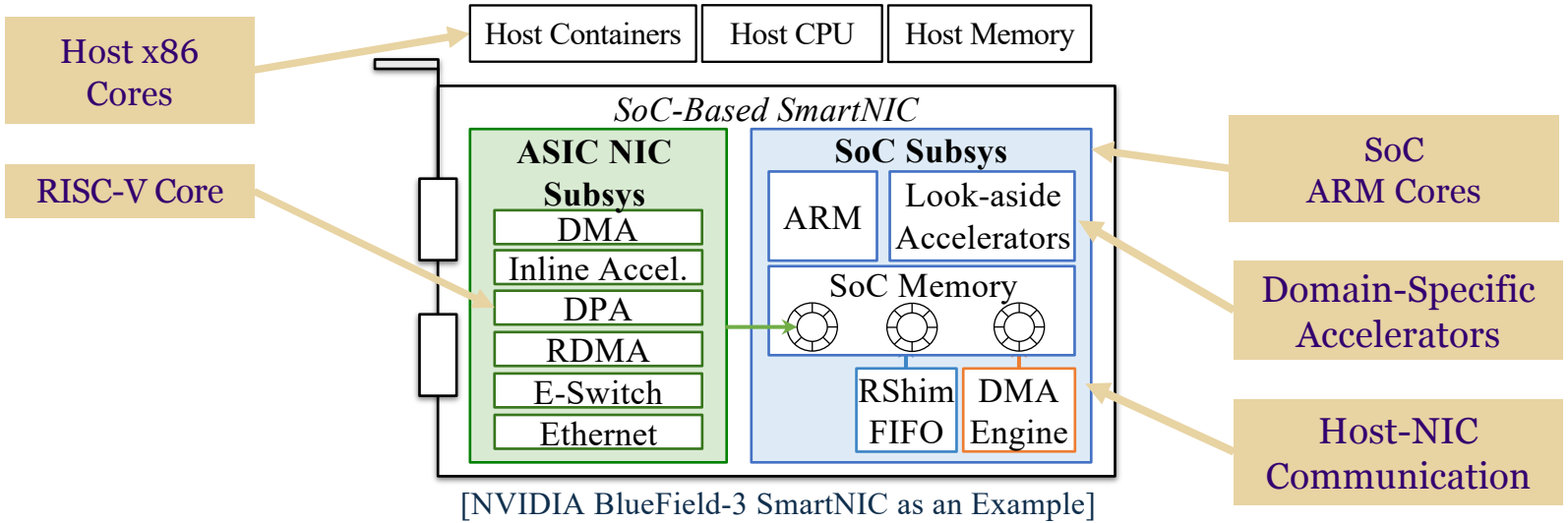

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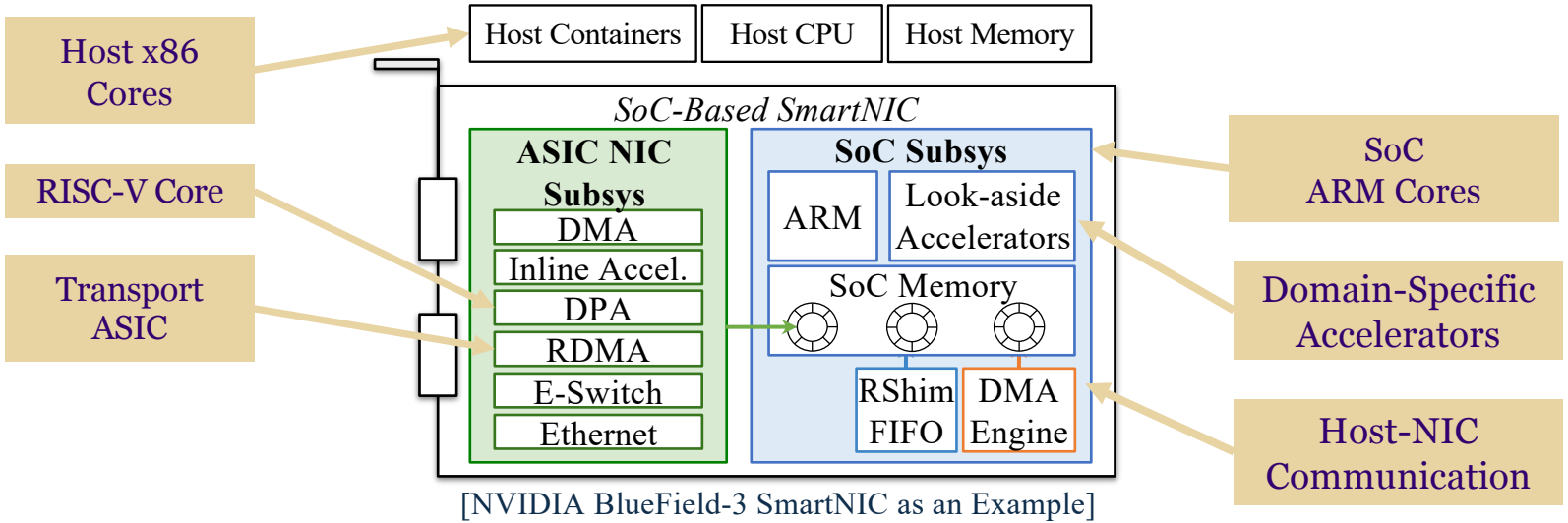

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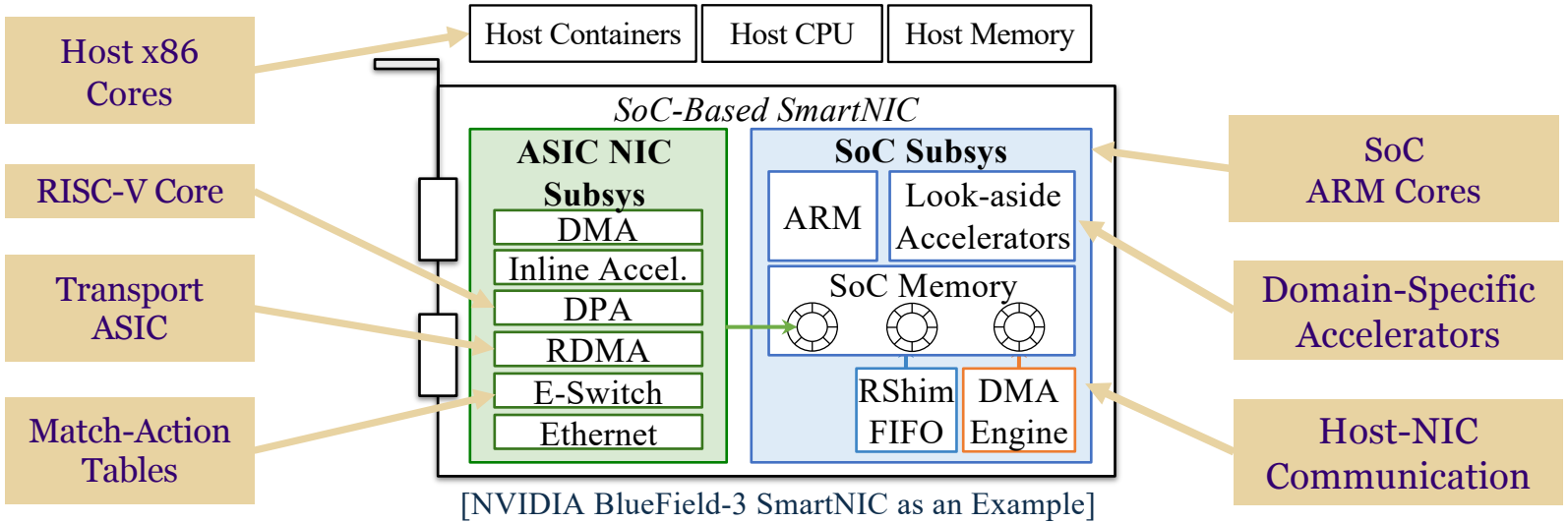

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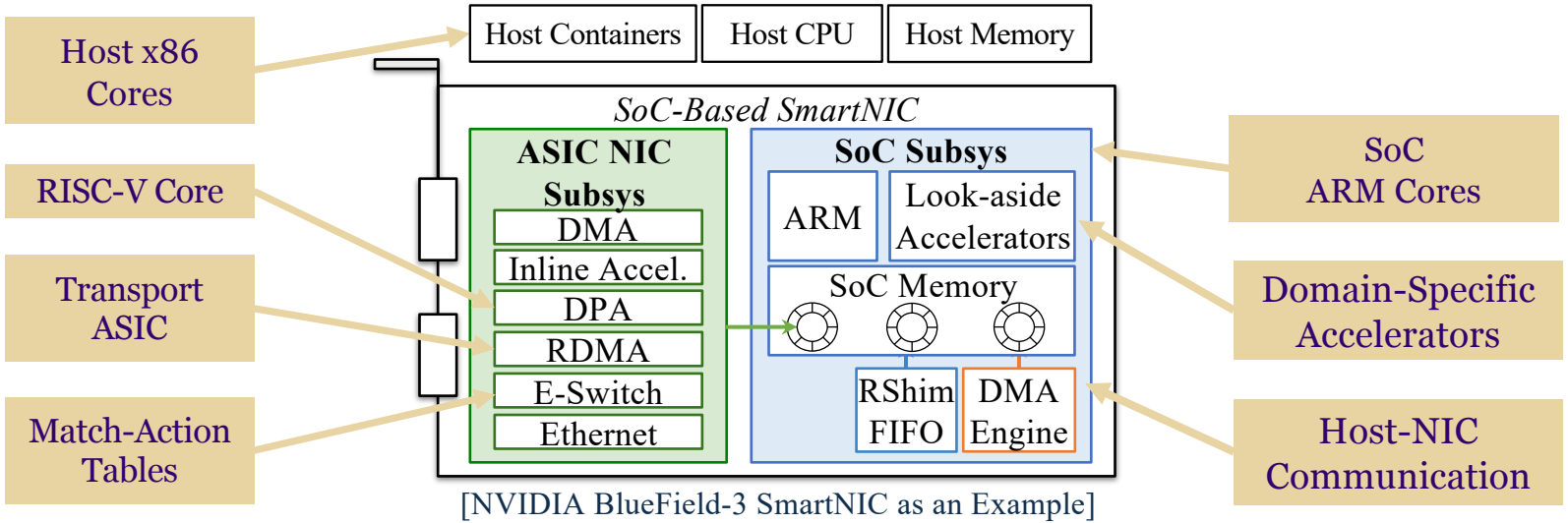

[NVIDIA BlueField-3 SmartNIC as an Example]

SR-IOV (2007 V1) was invented ~20 years ago
New devices and scenarios call for rethinking IOV

Overview (1/2): Signal and Data Plane Separation

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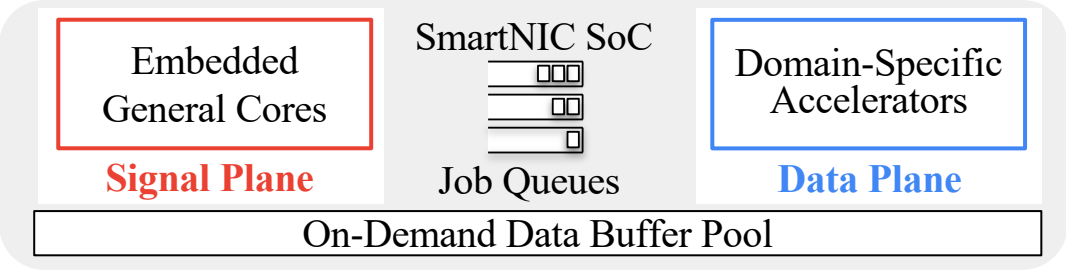

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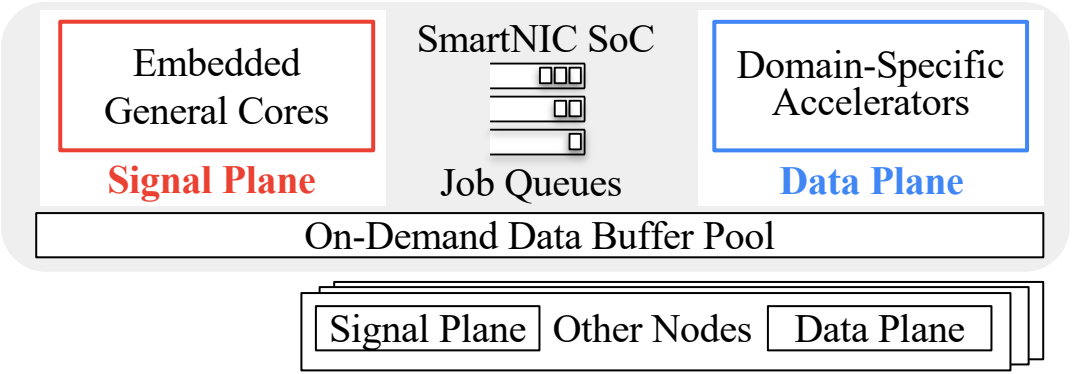

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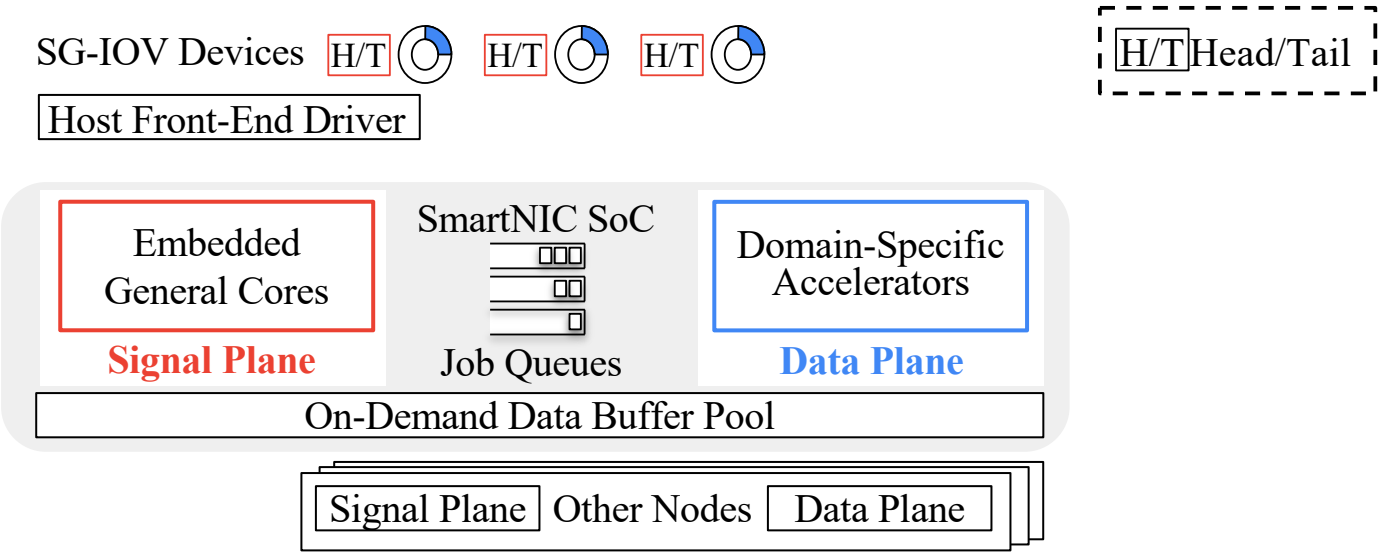

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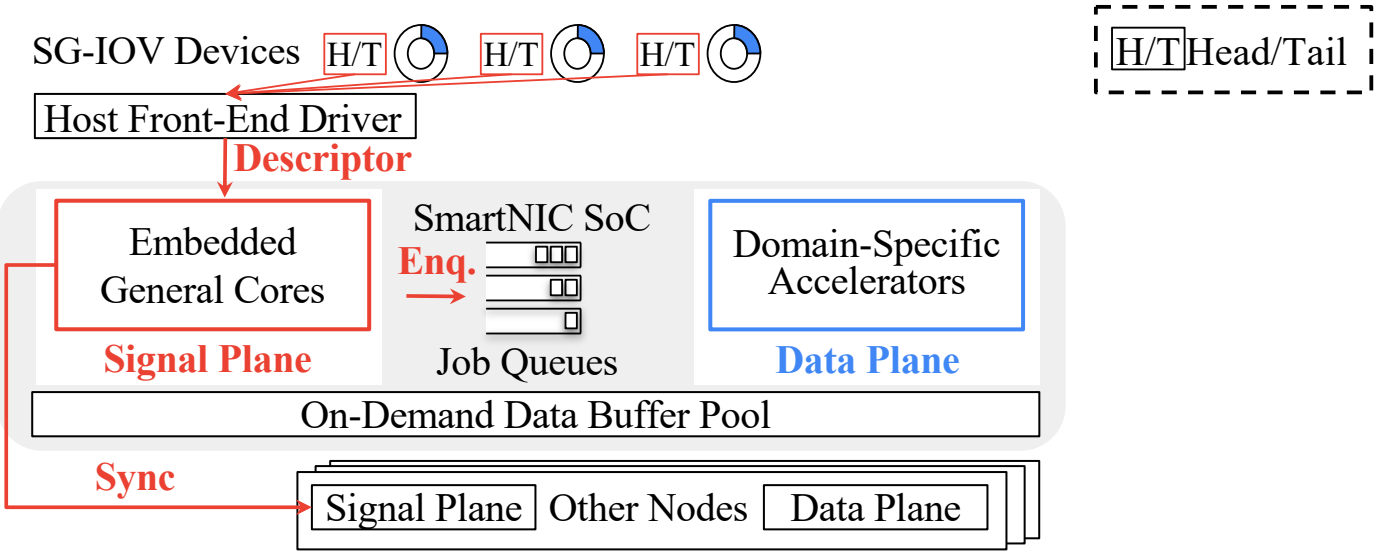

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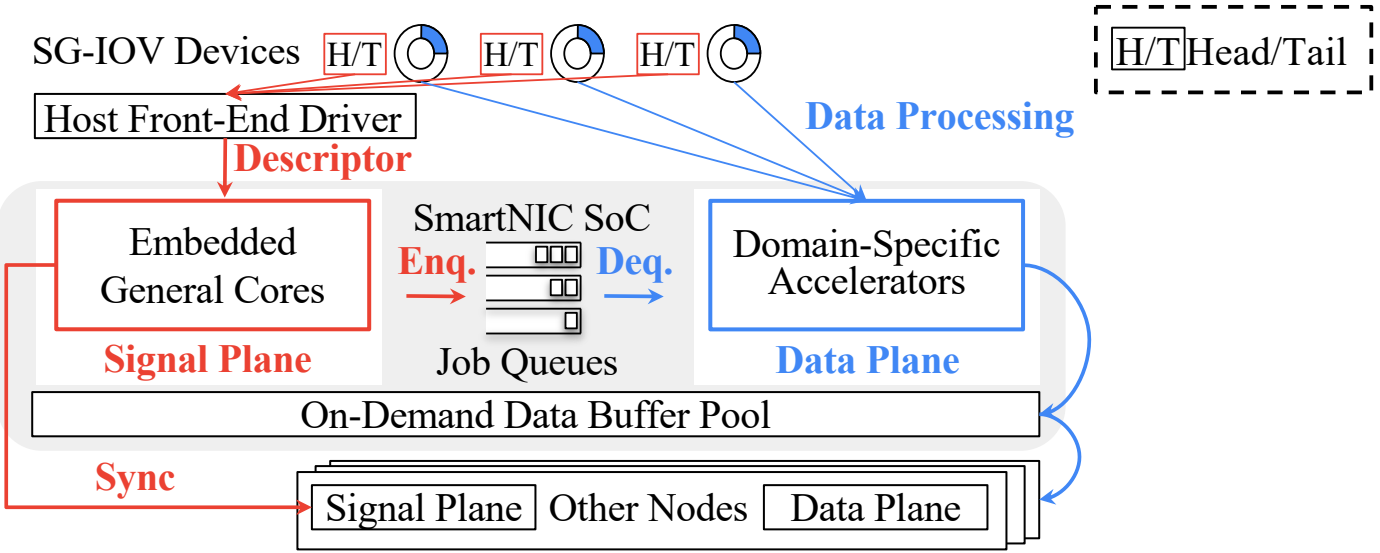

Overview (2/2): Chainable Execution over Warp Pipes

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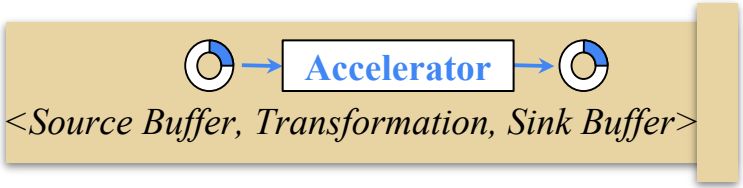
- *Warp Pipe:* Composition Unit for SG-IOV



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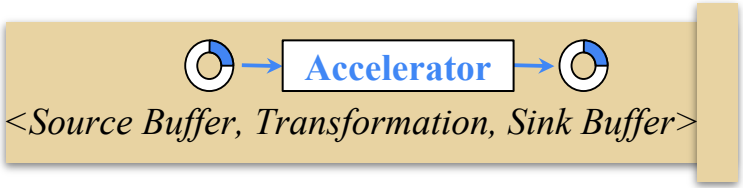

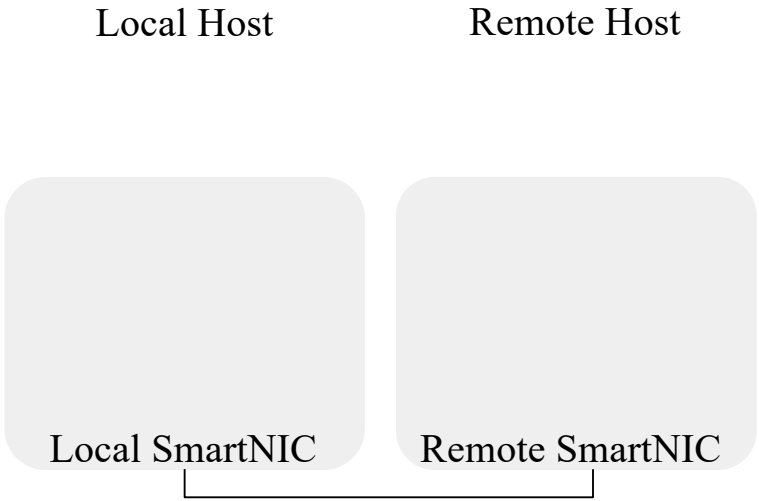

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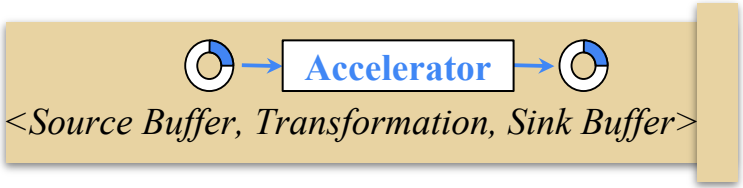

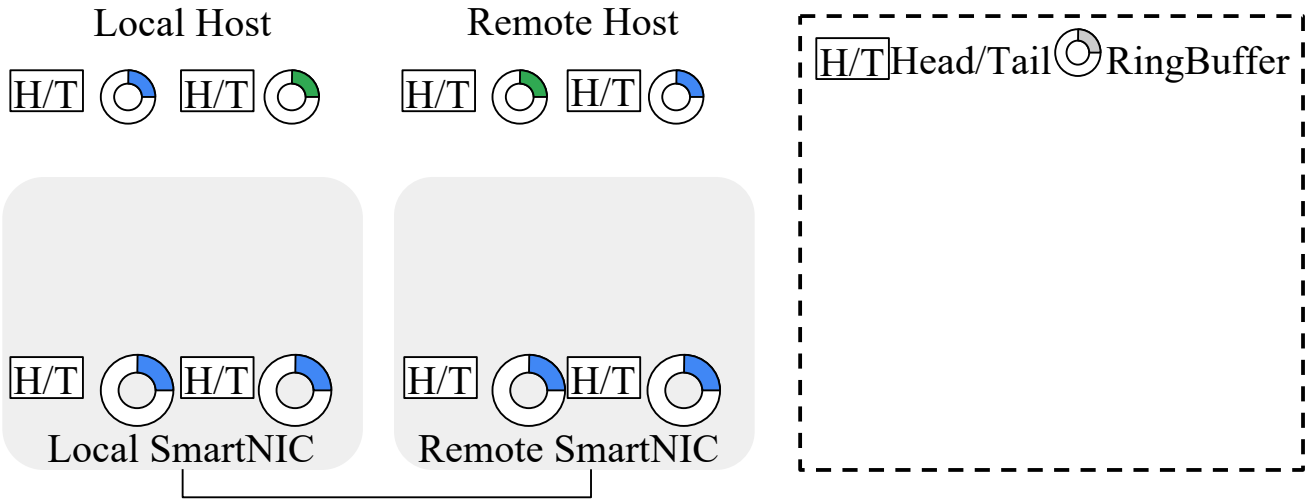

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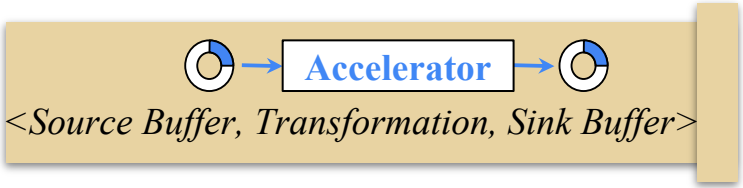

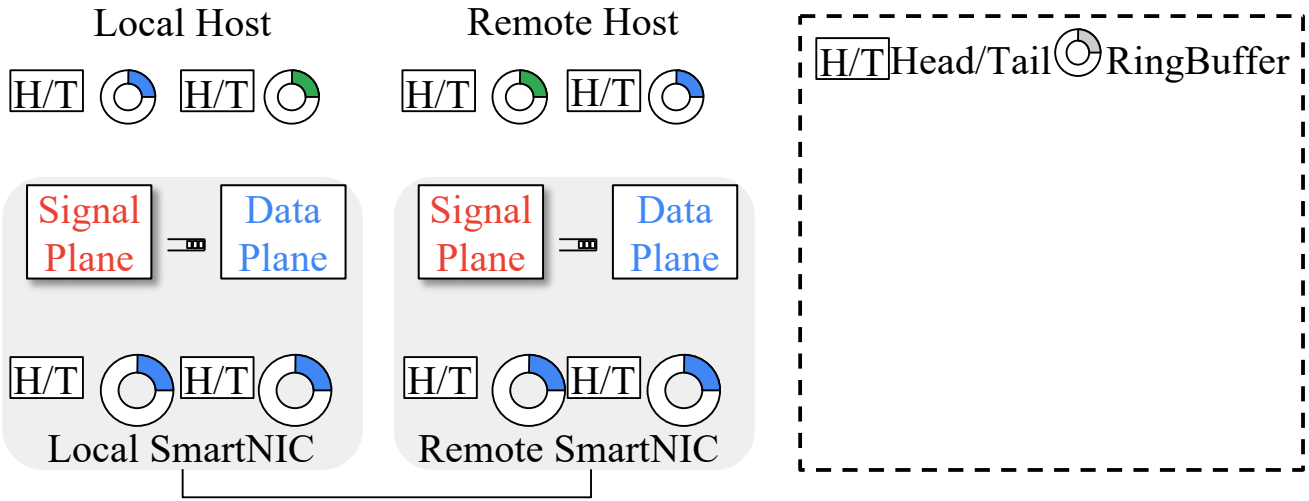

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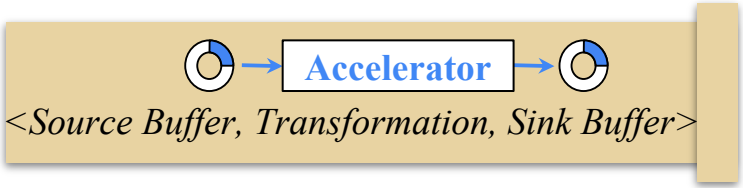

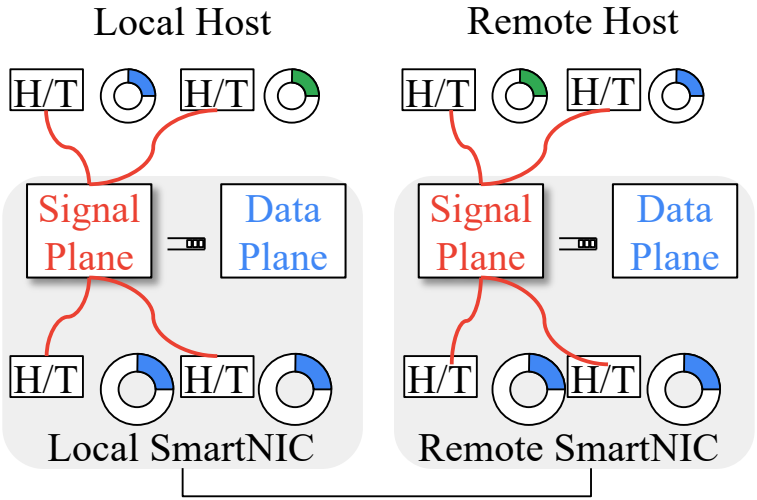

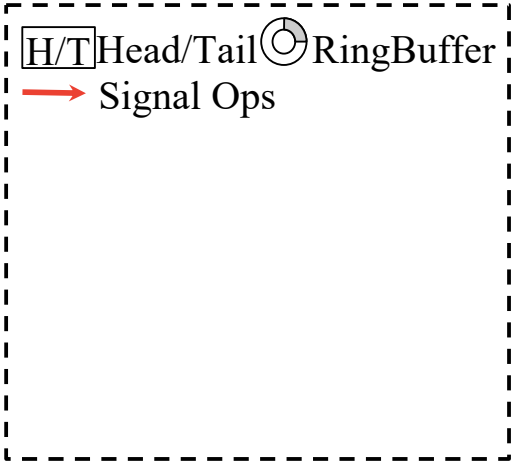

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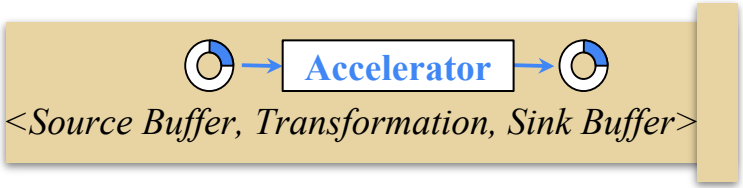

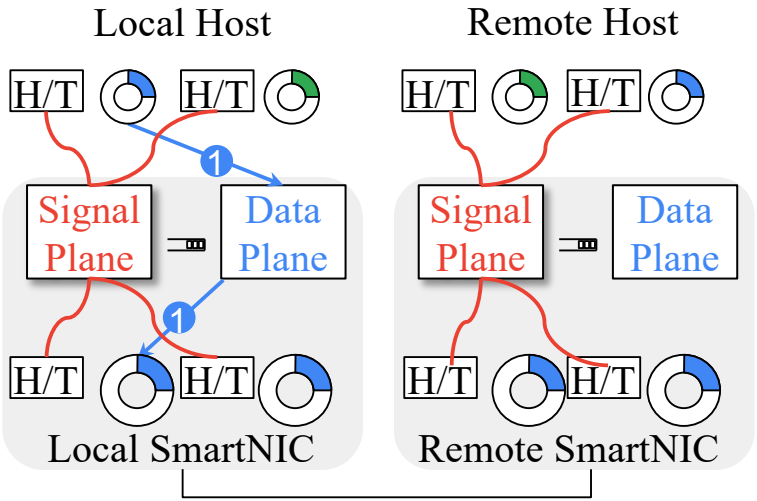

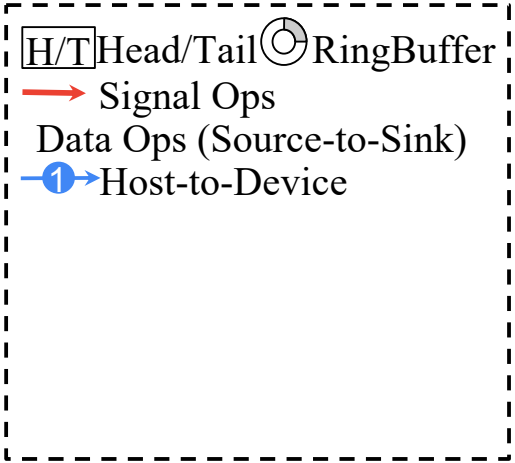

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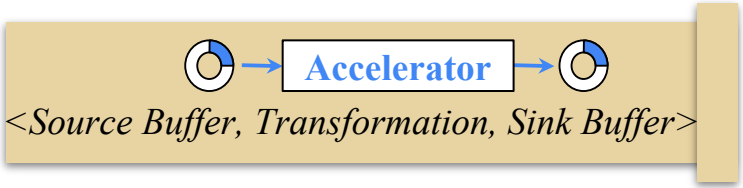

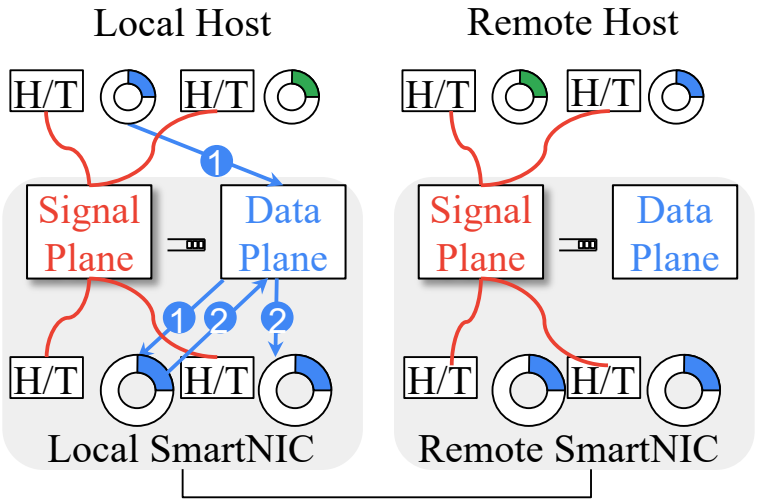

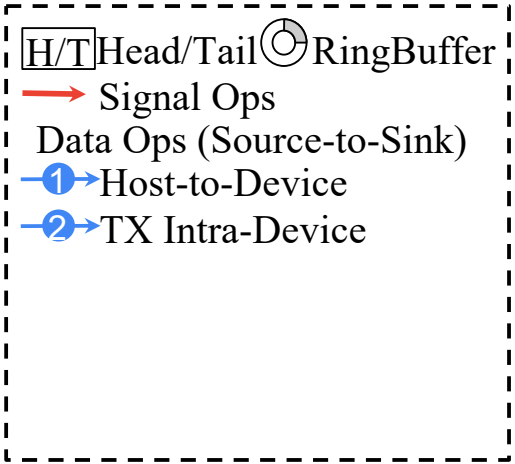

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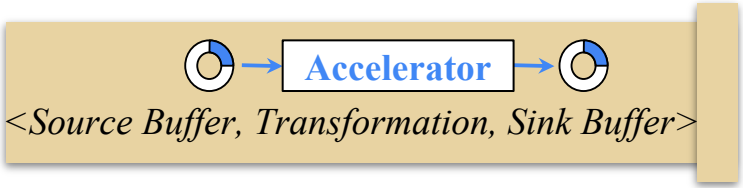

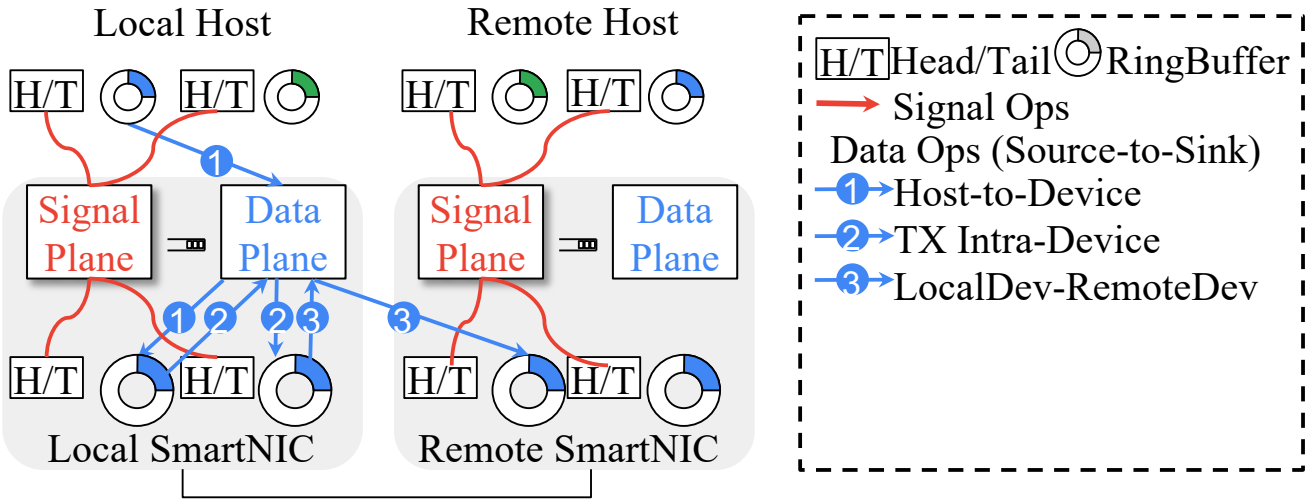

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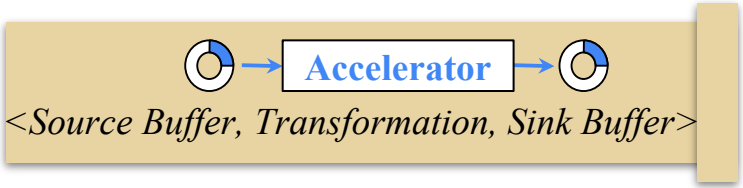

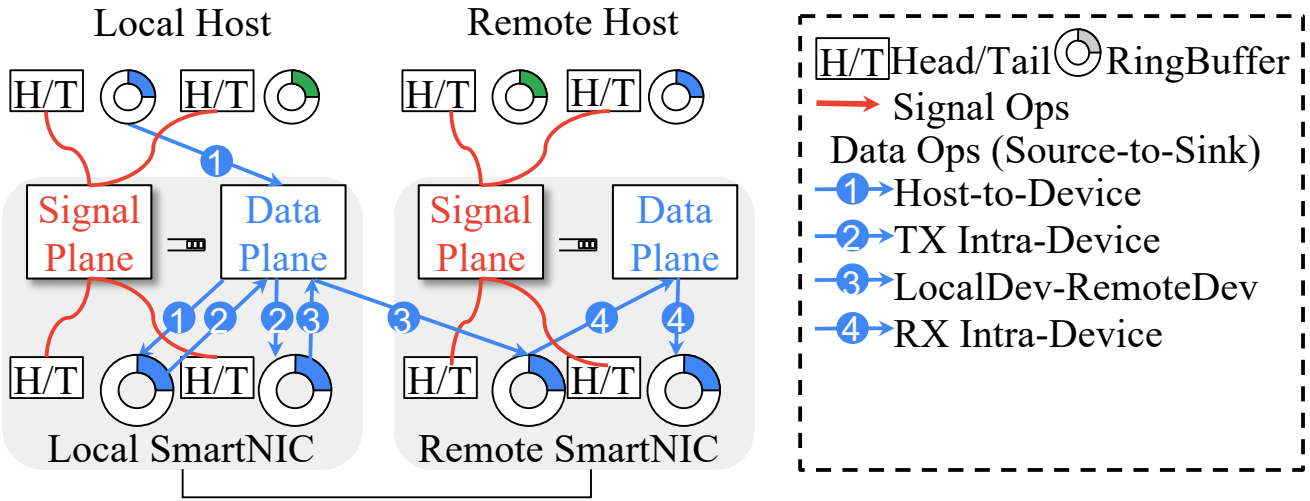

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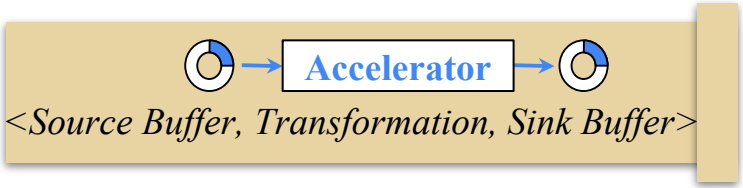

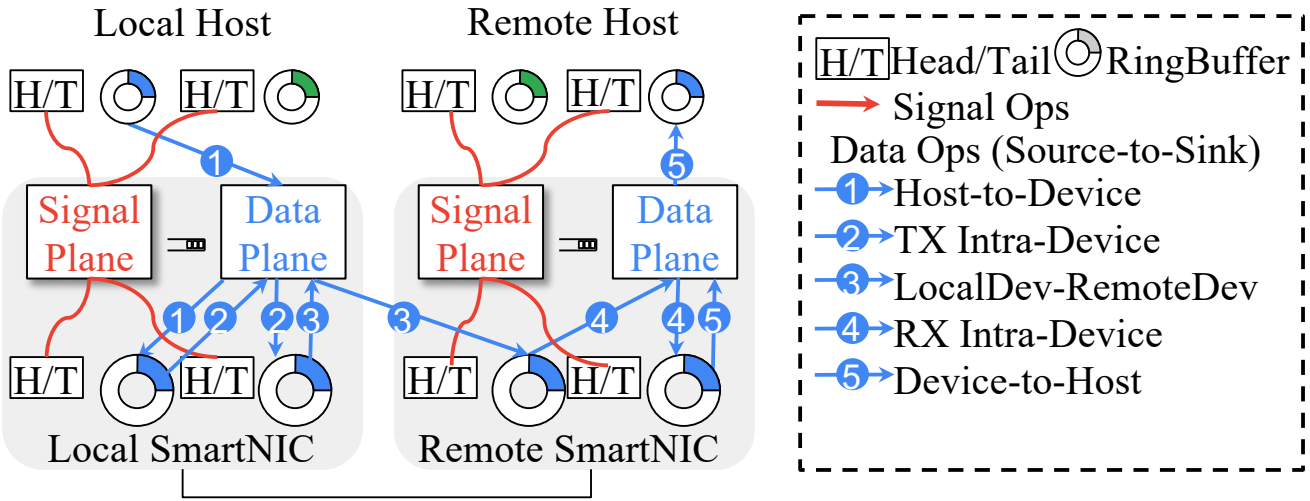

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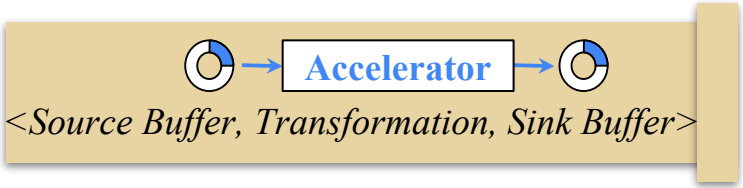

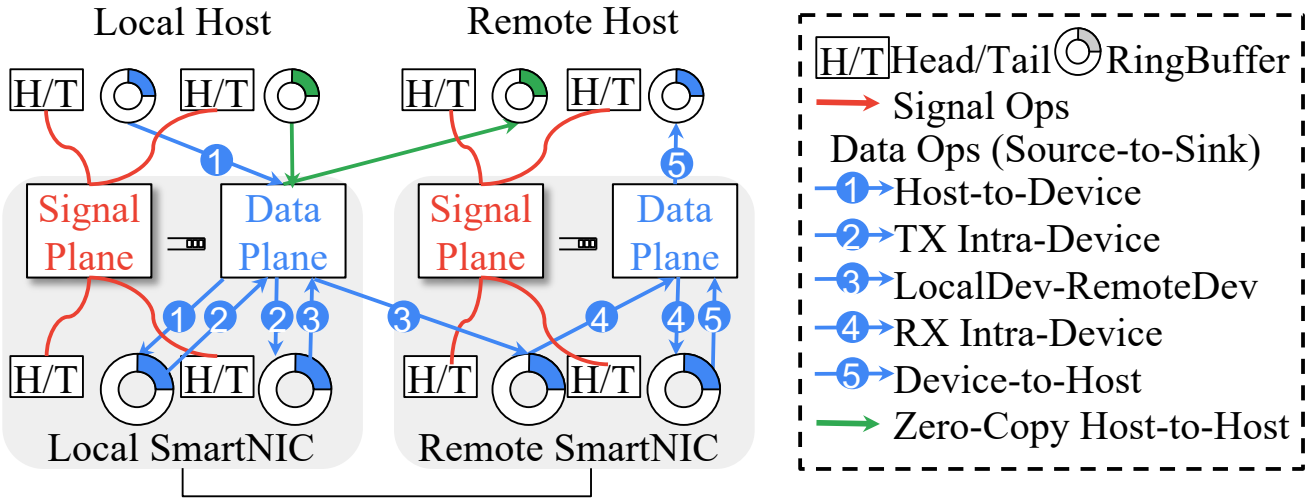

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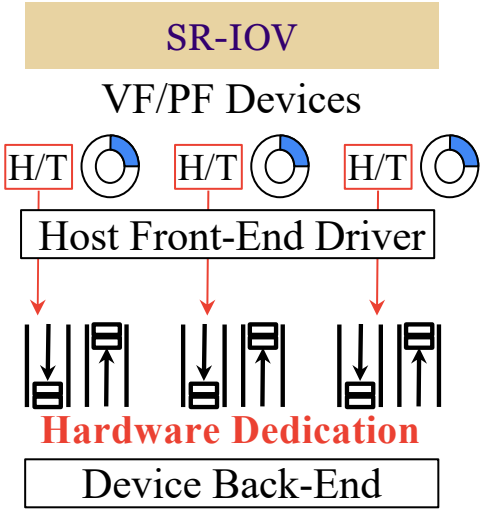

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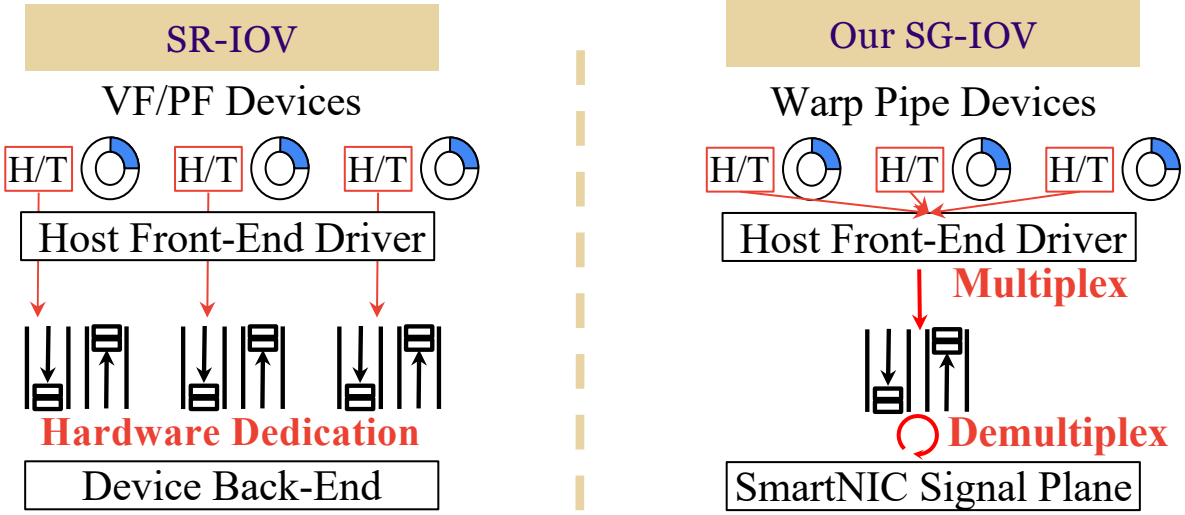

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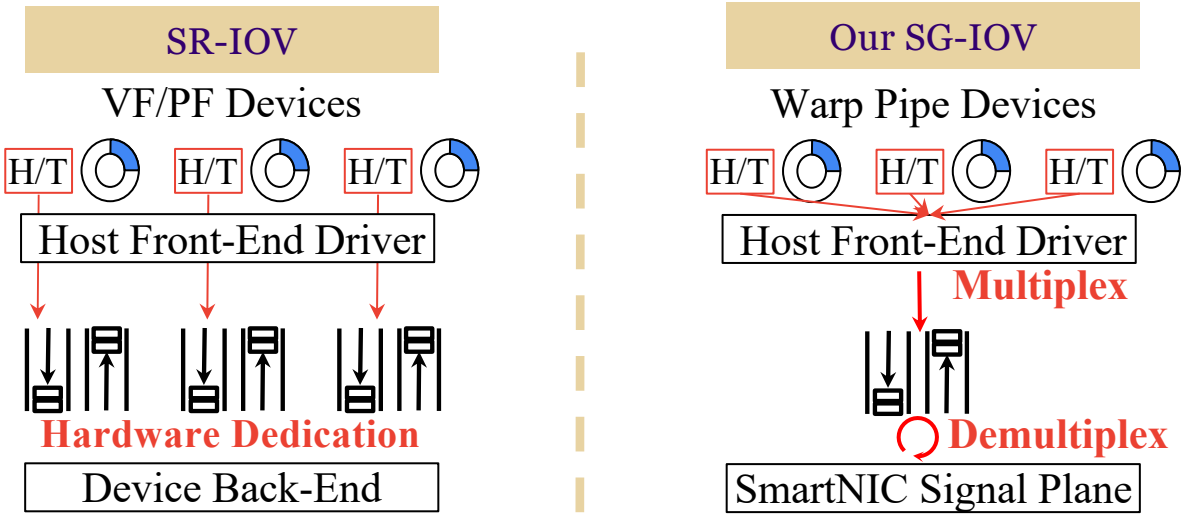

Approaching L5 socket scale, FIFO efficiency is crucial

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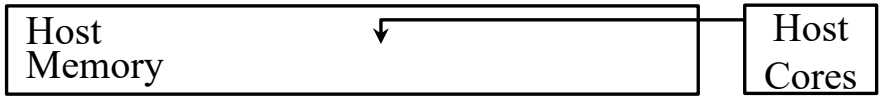

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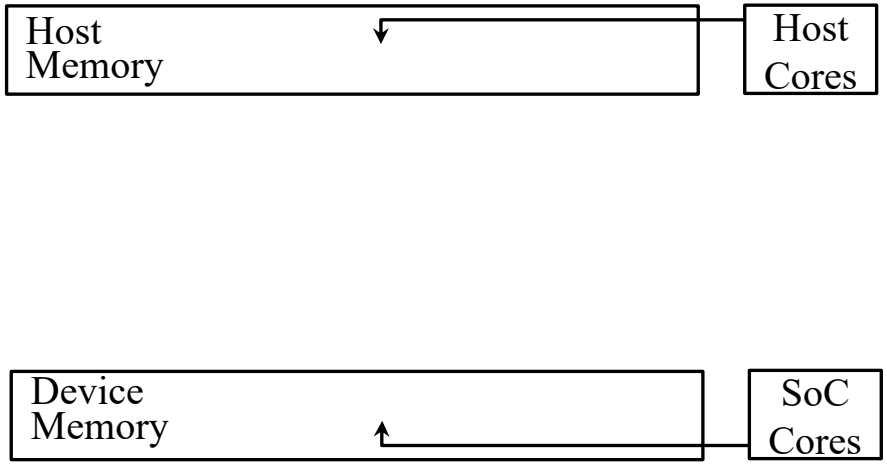

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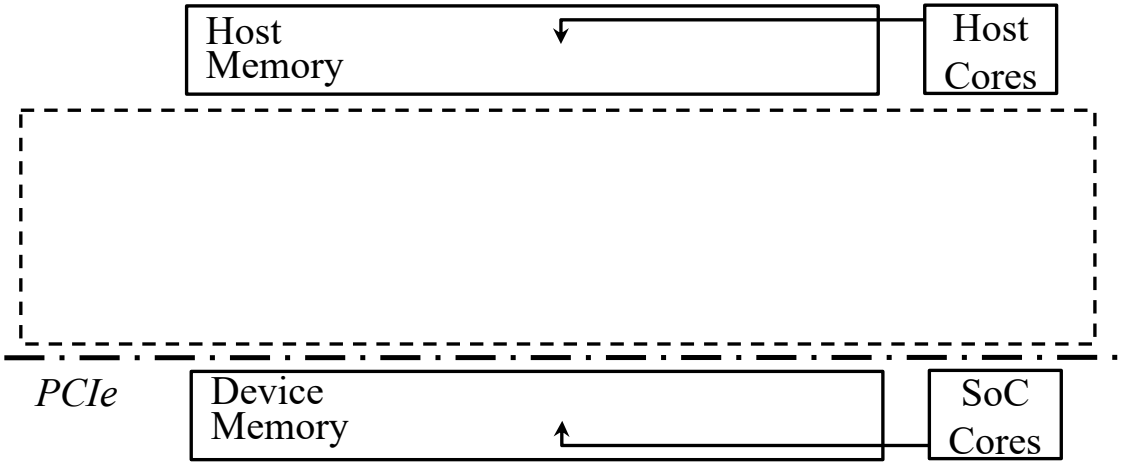

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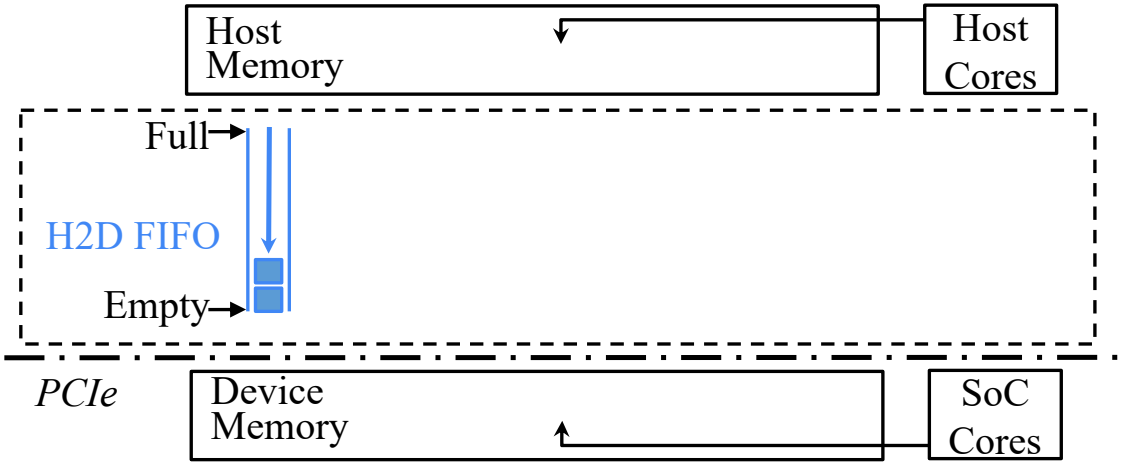

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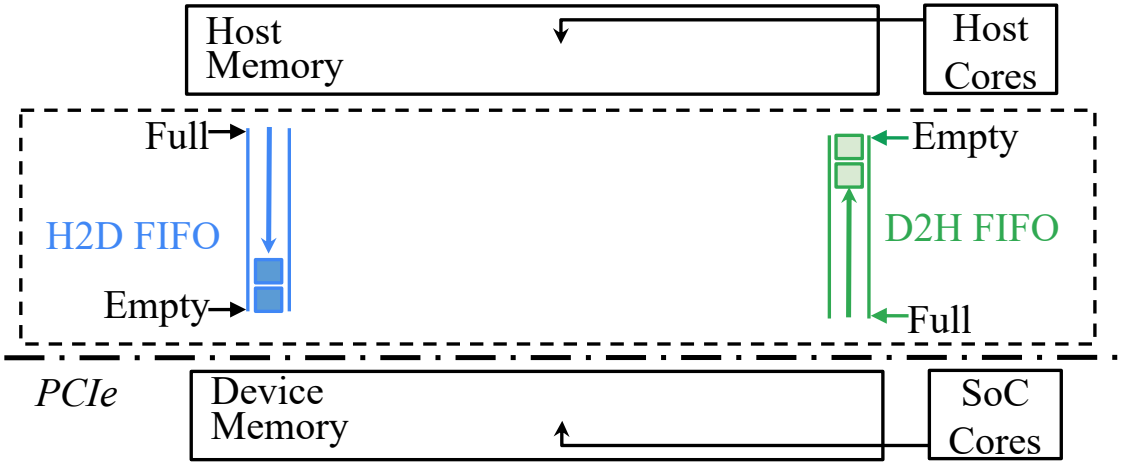

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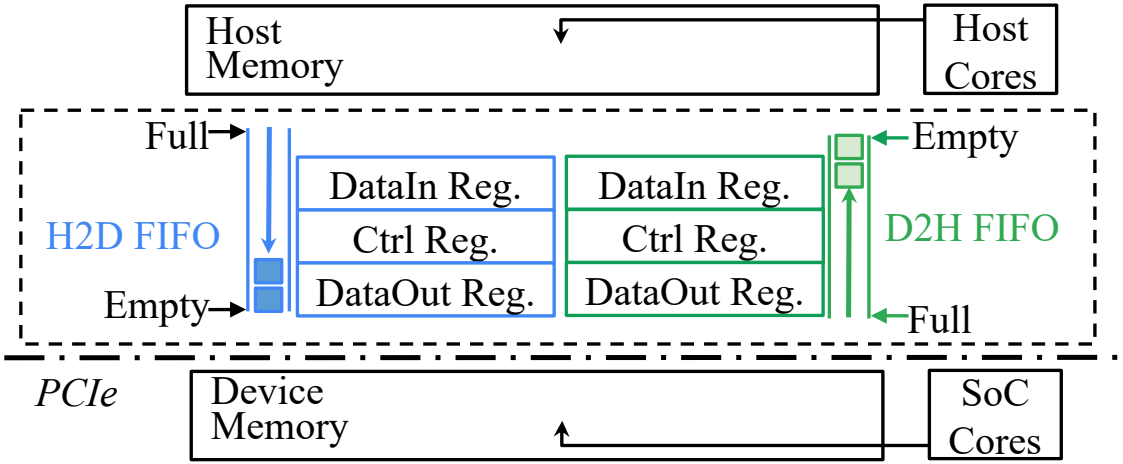

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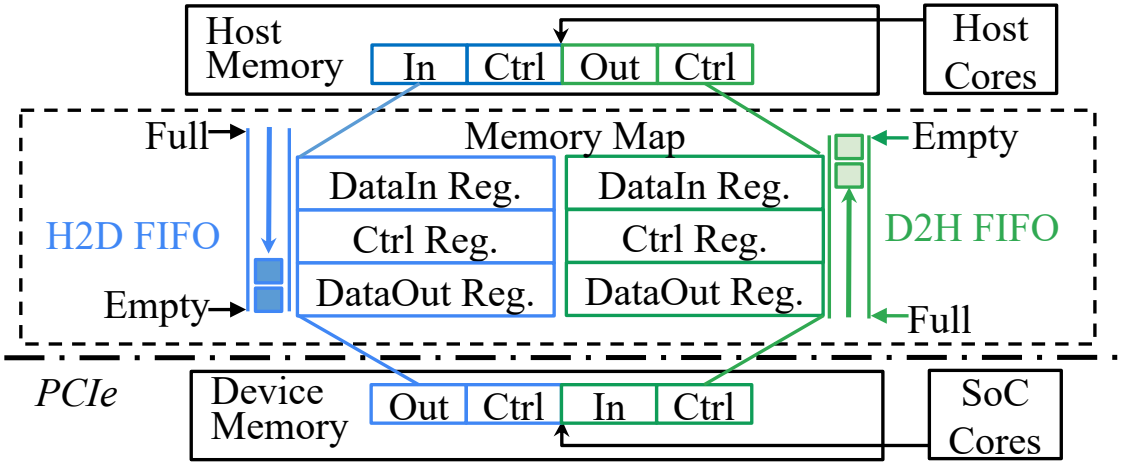

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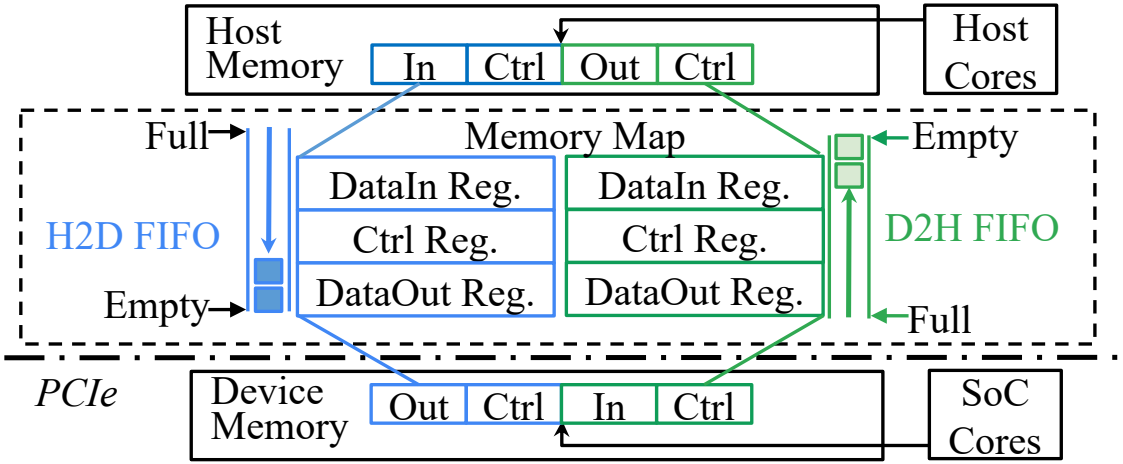

See the paper for detailed MMIO/RDMA primitives

Technique #2: Flexible Job Generation

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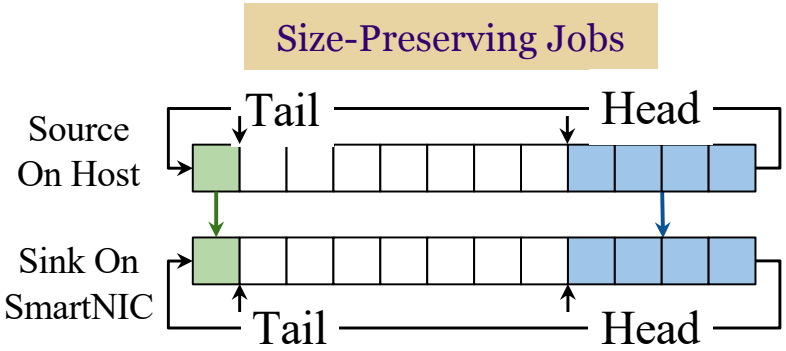

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- Determine Source/Sink Chunks for Diverse Transformations (*e.g.*, DMA, Encrypt)
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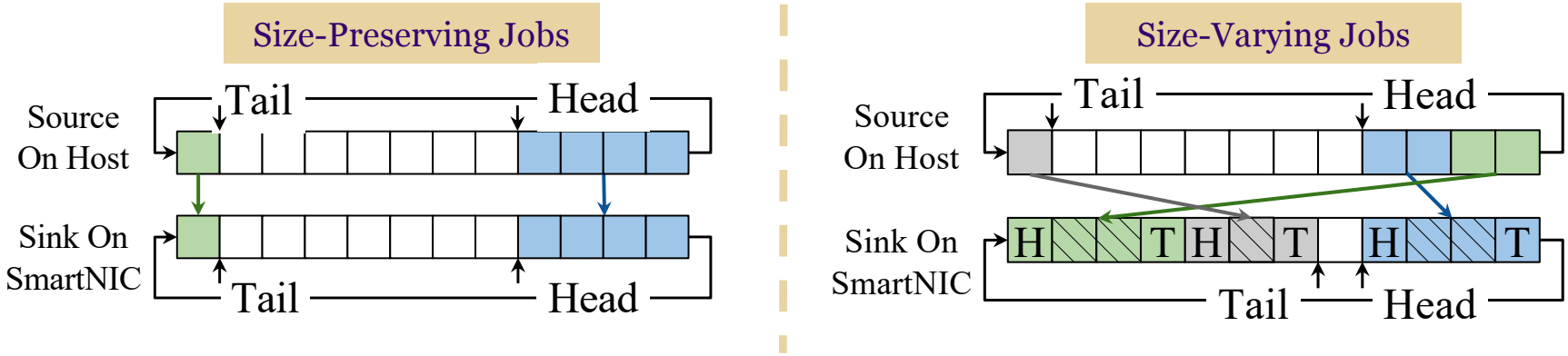
    - 2×2×2 = 8 cases: <source wrap or not × sink wrap or not × size change or not>



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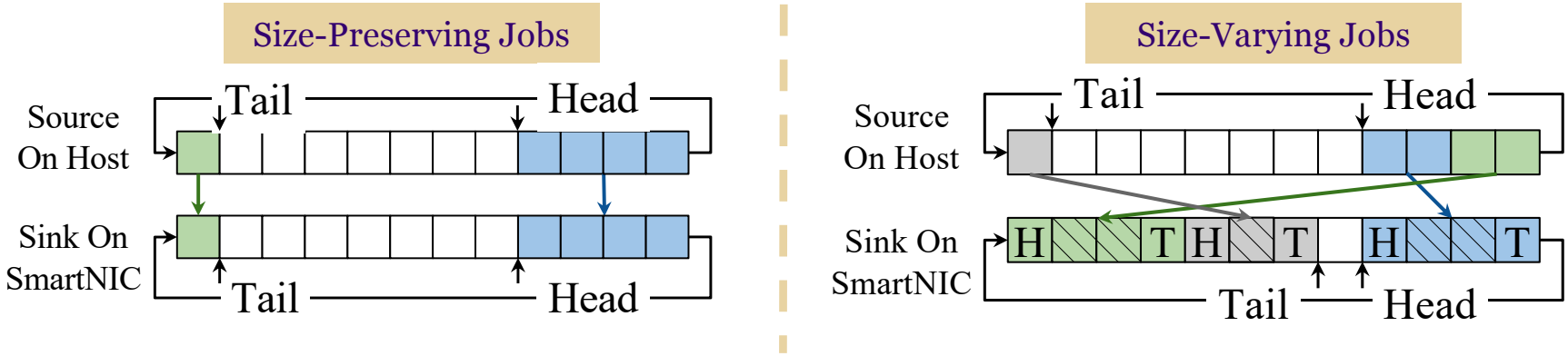

See the paper for the *Recursive Strategy* that covers all cases

Technique #3: Fine-Grained HW Virtualization (1/2)

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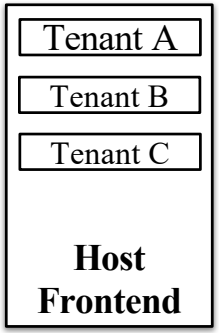

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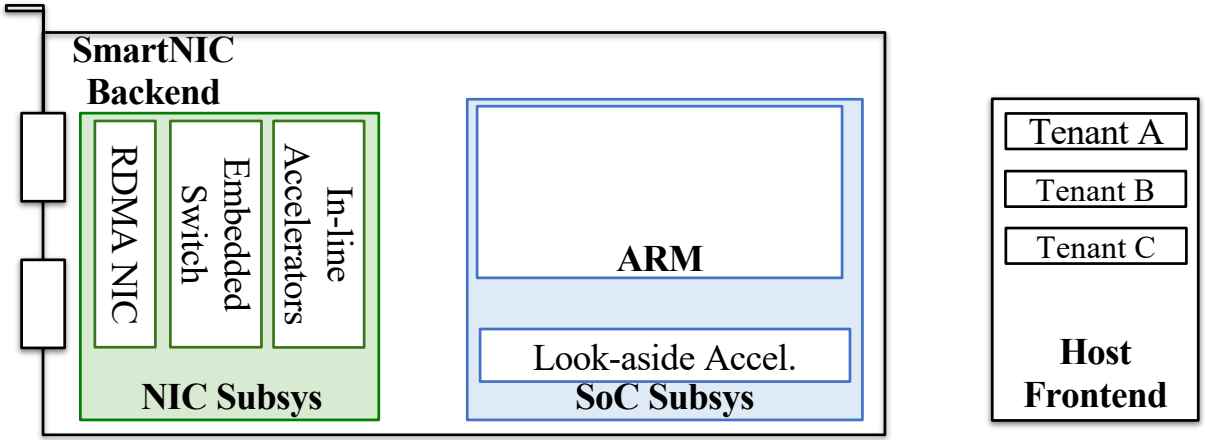

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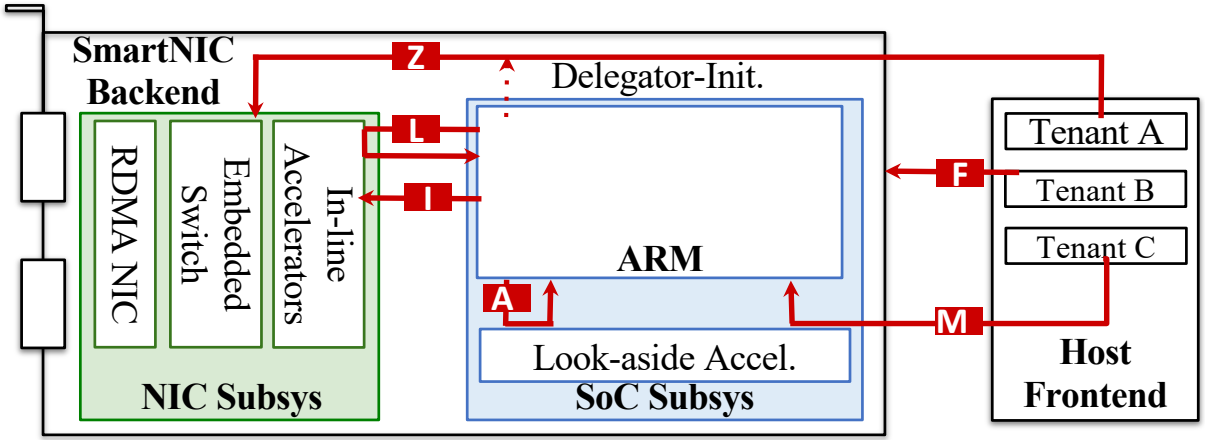

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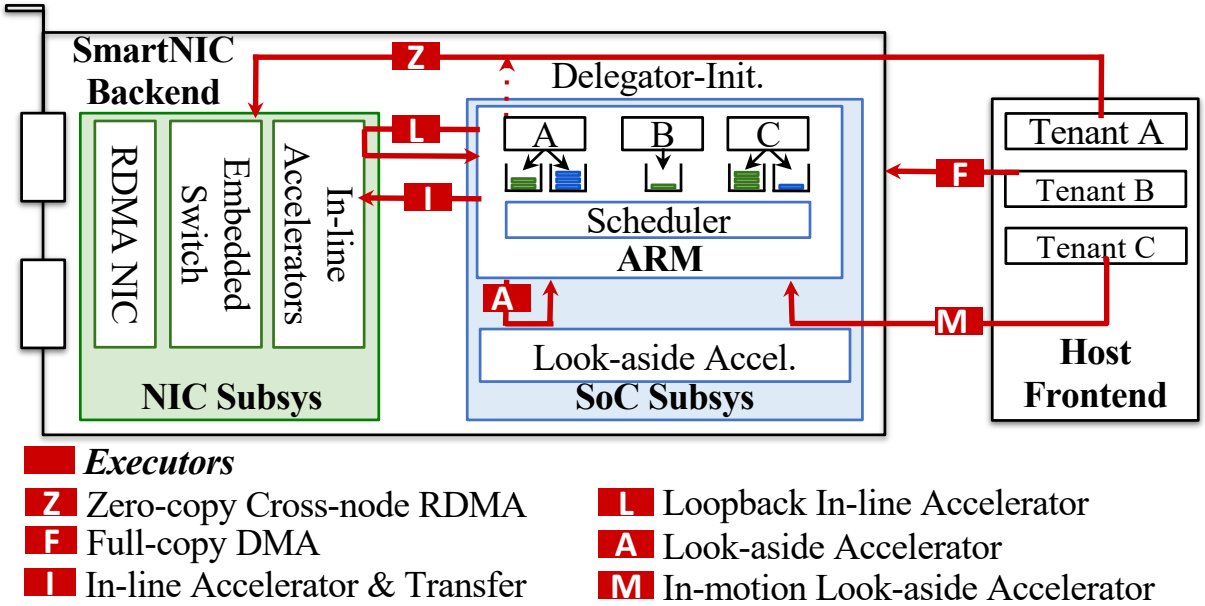

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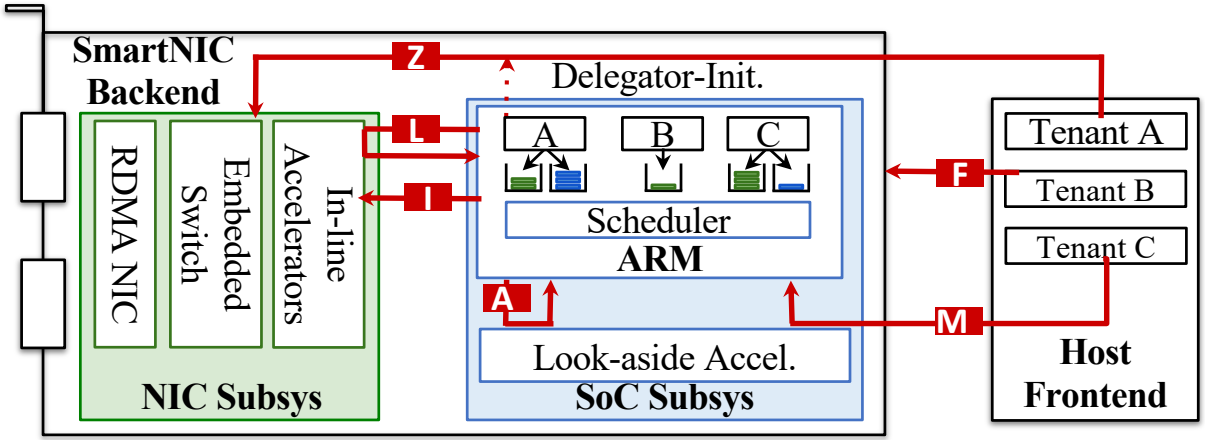

Next, how do we use such a queuing system to schedule jobs?

Technique #3: Fine-Grained HW Virtualization (2/2)

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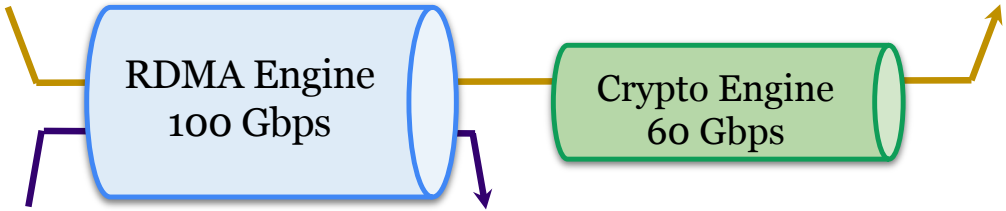

Dominant Resource
Tenant-A: {RDMA, Crypto}
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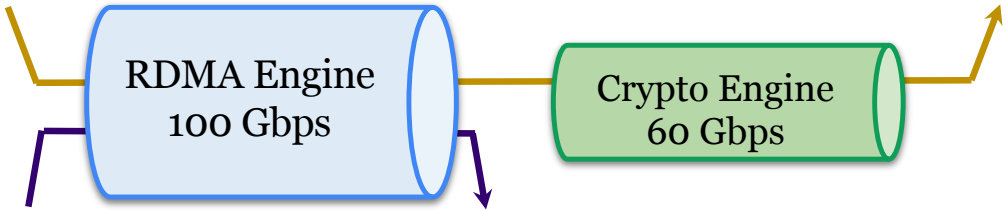
Technique #3: Fine-Grained HW Virtualization (2/2)

- Dominant Resource Fairness (DRF) Policy Specialized by SG-IOV
  - ***Equal-Bandwidth Demand*:** Multi-accelerator tenants consume the same BW on all accelerators



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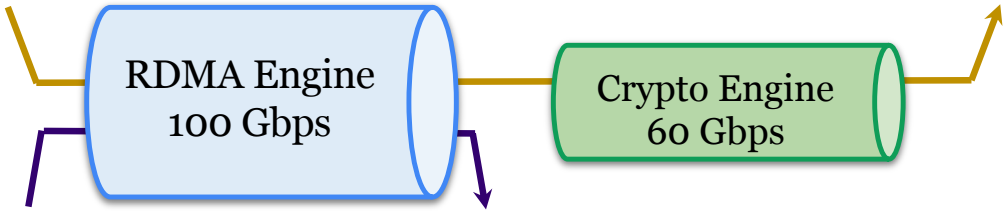

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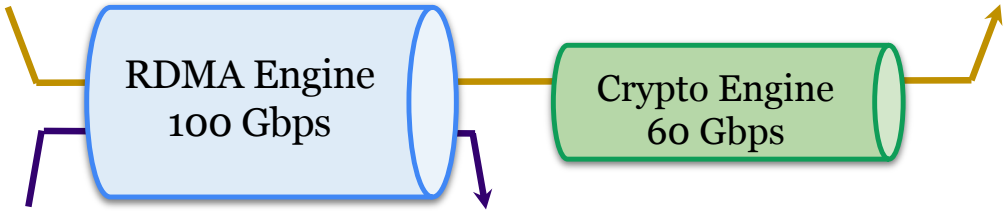

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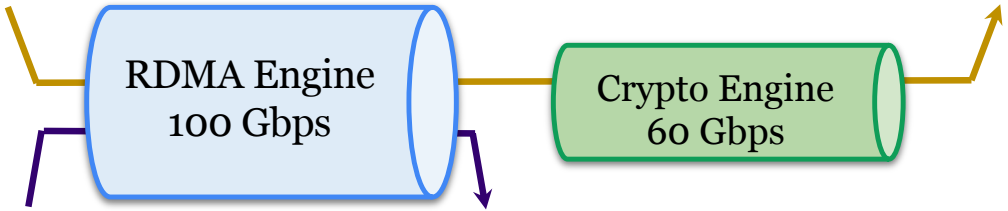

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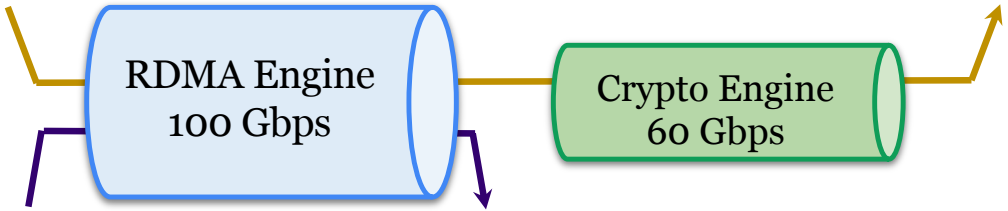

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See the paper for the formal mathematical analysis

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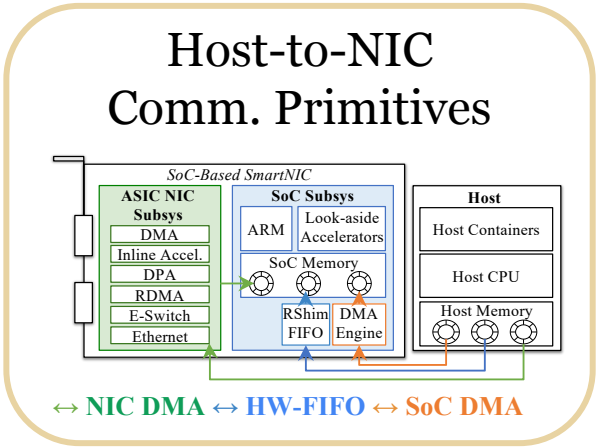

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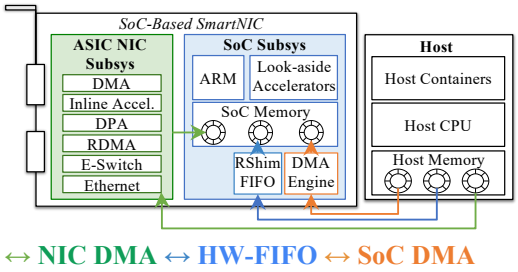
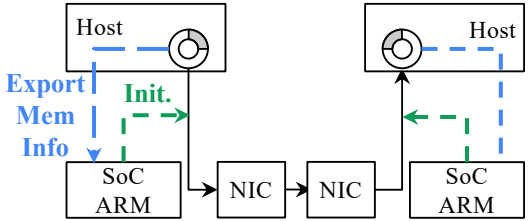
Host-to-NIC Comm. Primitives



SoC-Delegated Zero-Copy



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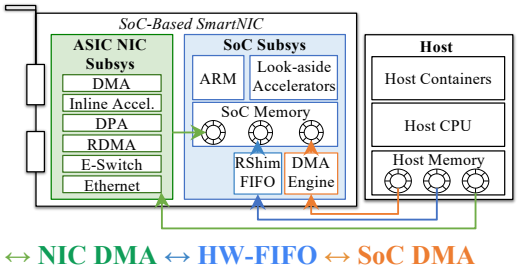

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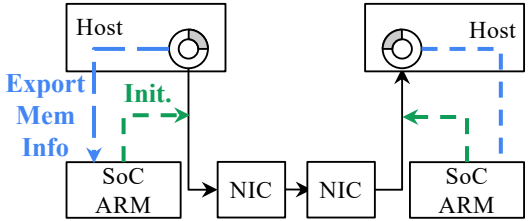
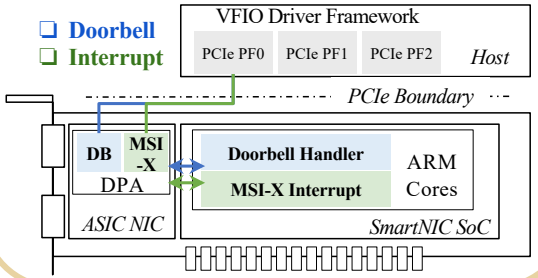


PCIe Device Emulation



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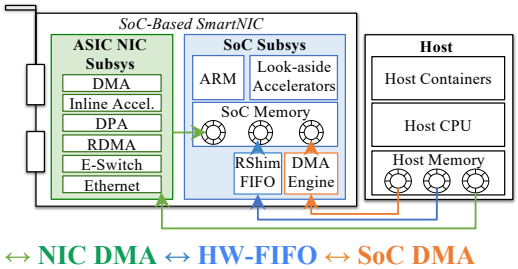

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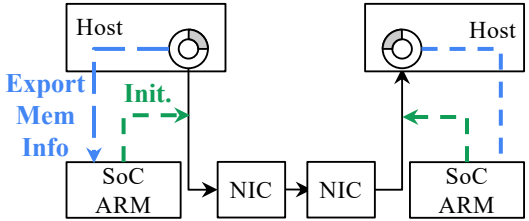

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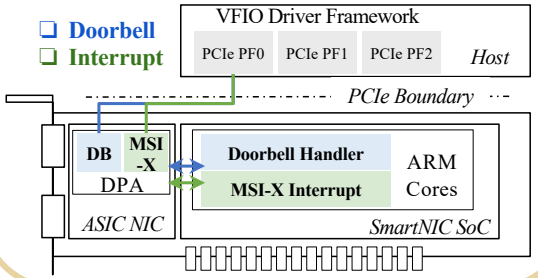

See the paper for detailed characterization

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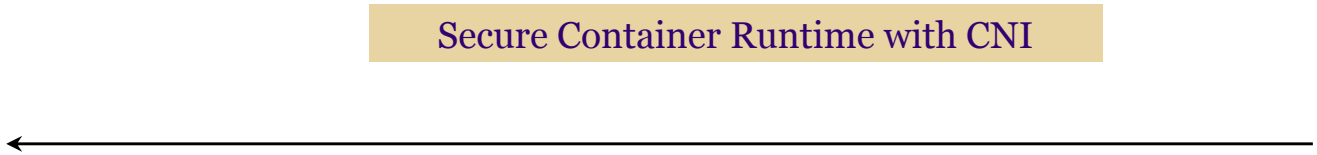

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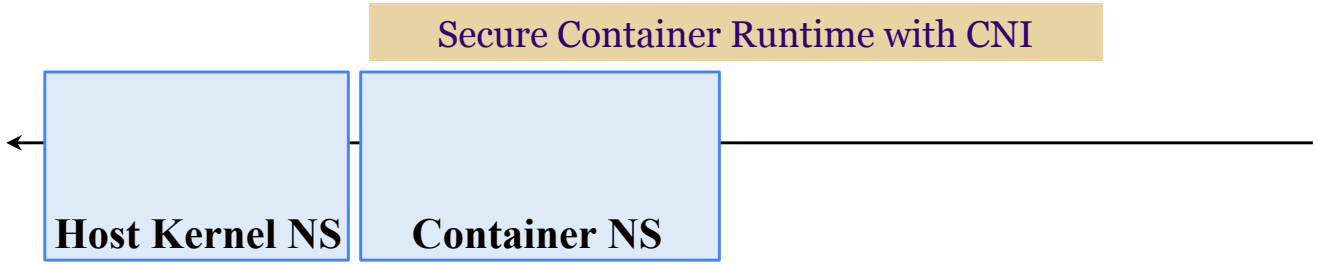

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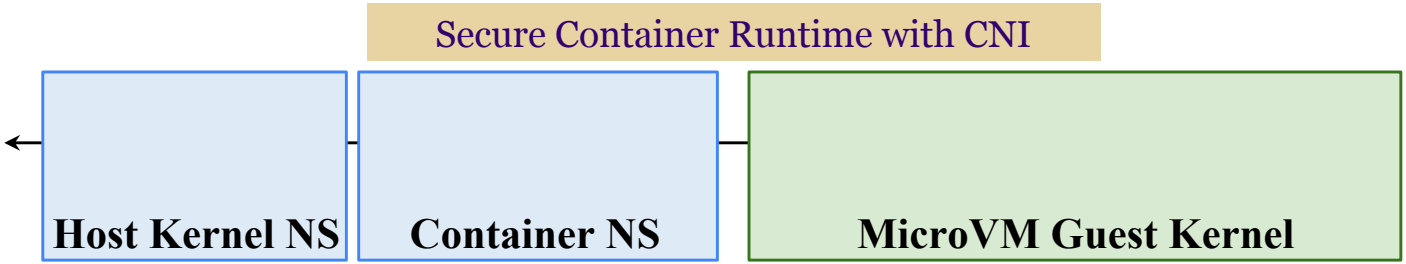

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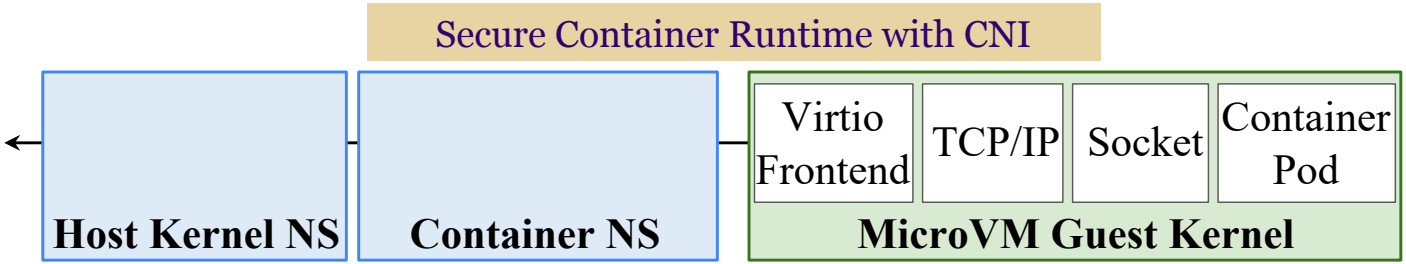

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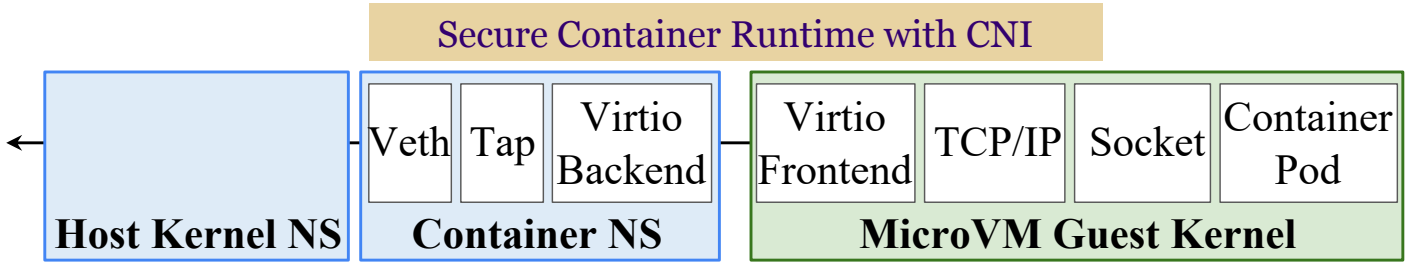

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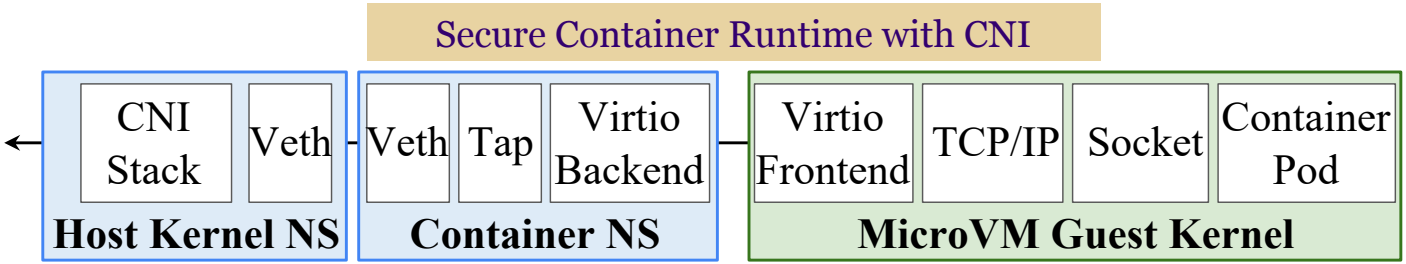

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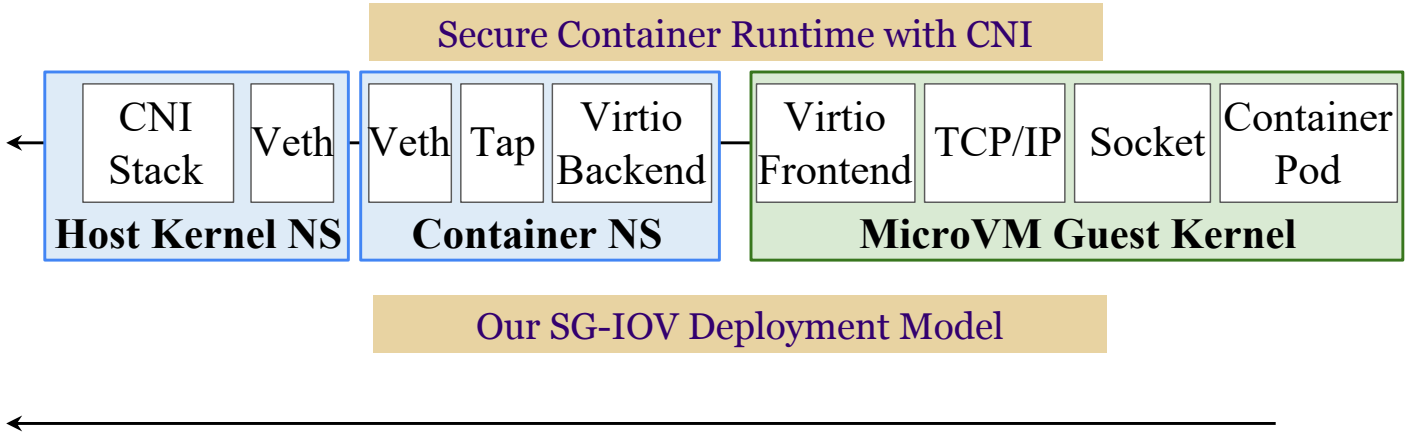

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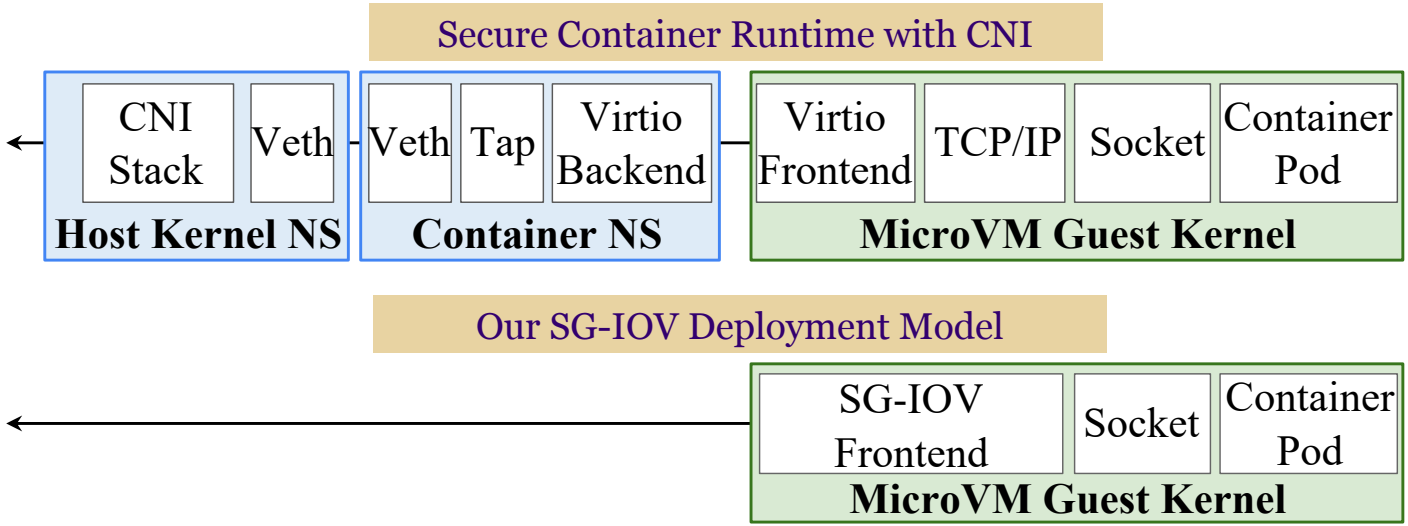

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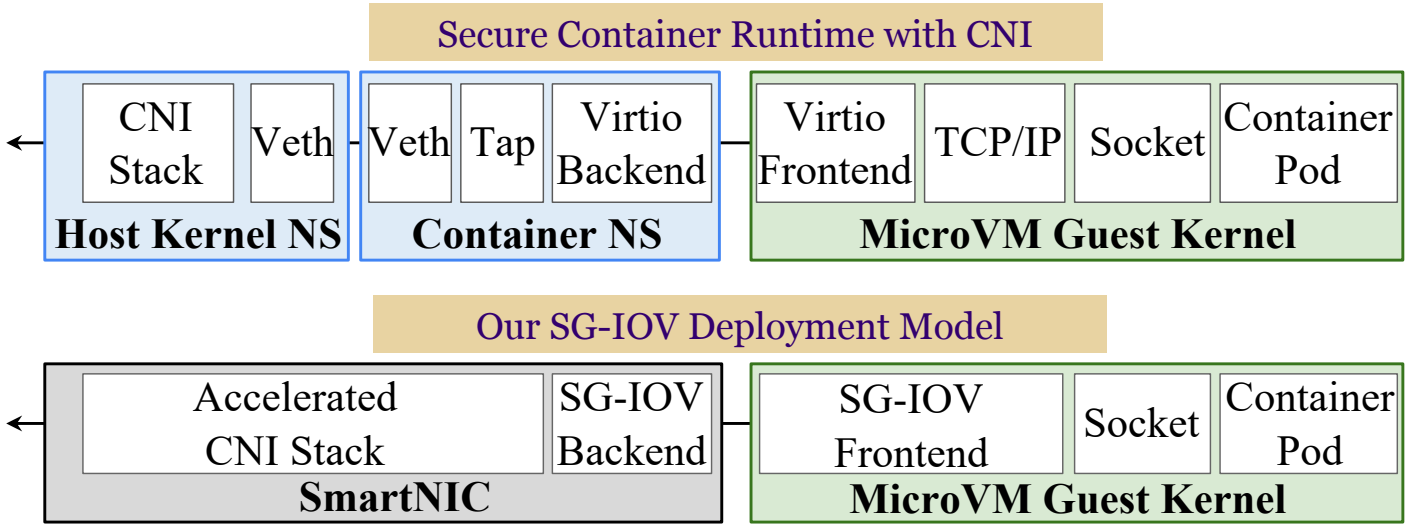

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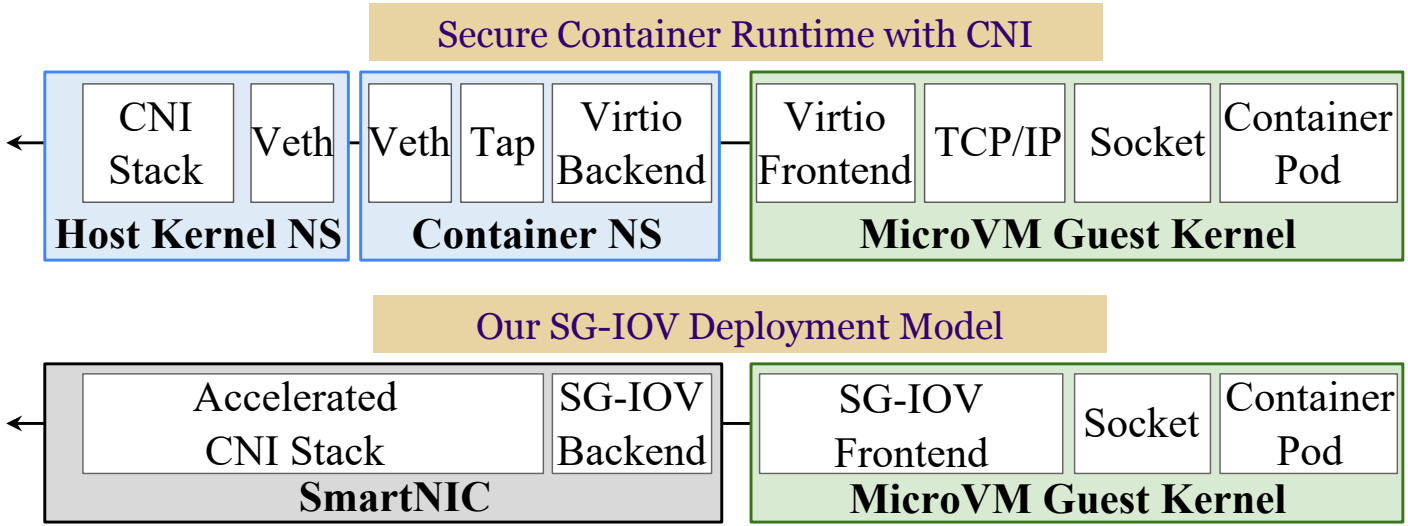

See the paper for SGIOV-CNI support for traditional containers

Evaluation: Micro-Benchmarking SG-IOV

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  - Two connected servers (NVIDIA BlueField-3 with a 100GbE switch)
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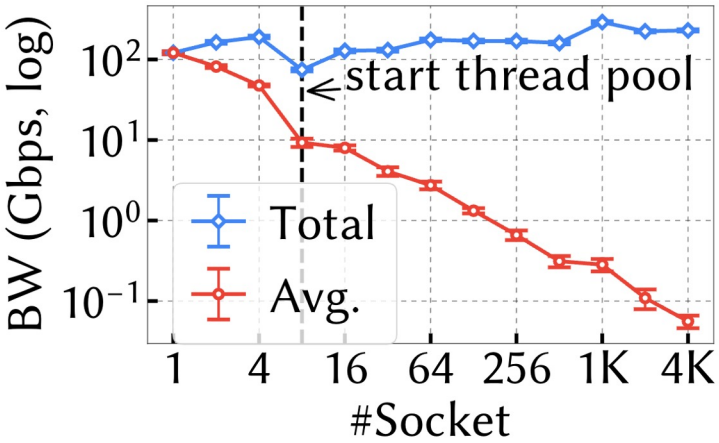

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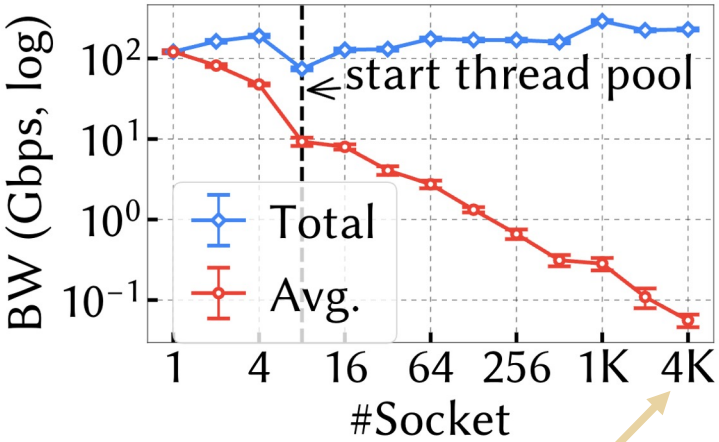

Scales up to 4K devices, approaching socket scale

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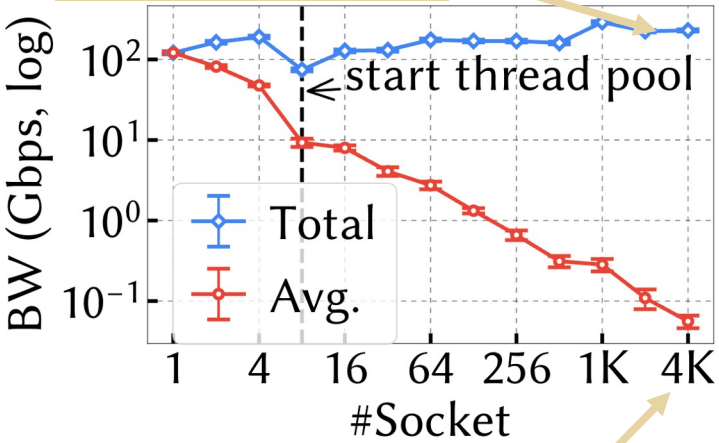

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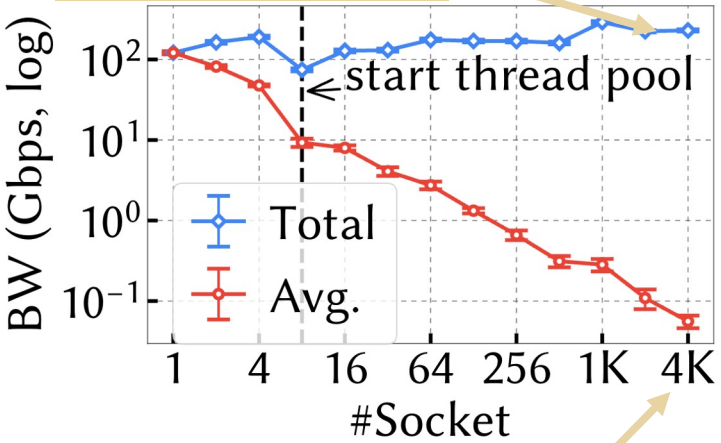

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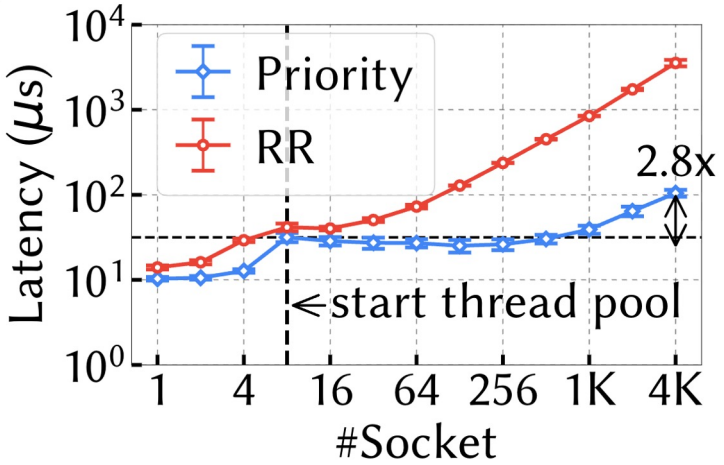

Evaluation: Micro-Benchmarking SG-IOV

- Test setup
  - Two connected servers (NVIDIA BlueField-3 with a 100GbE switch)
  - Standard POSIX send()/recv() over Warp Pipes
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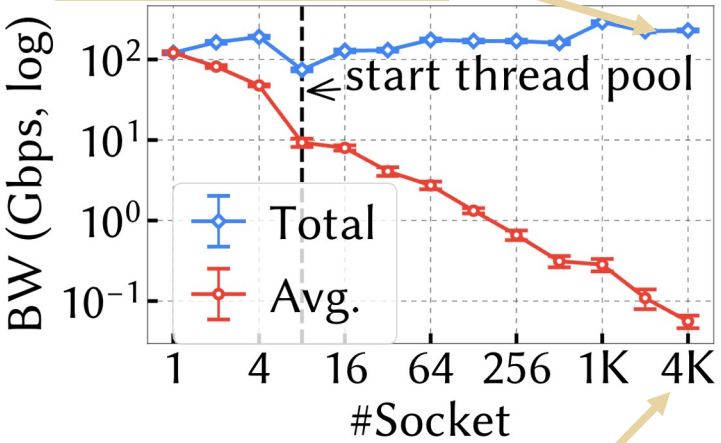

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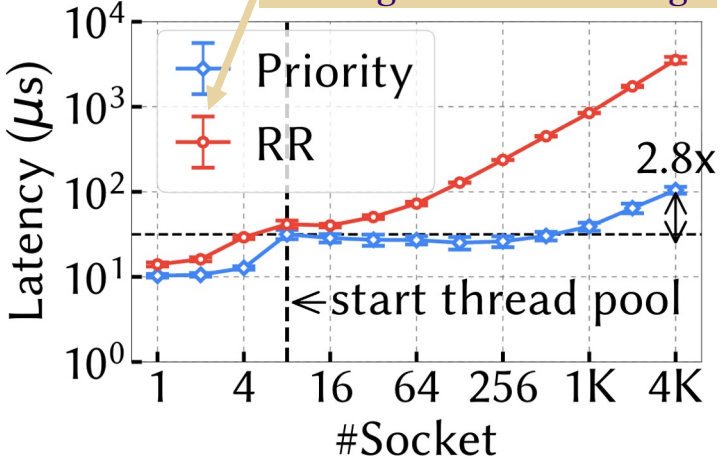

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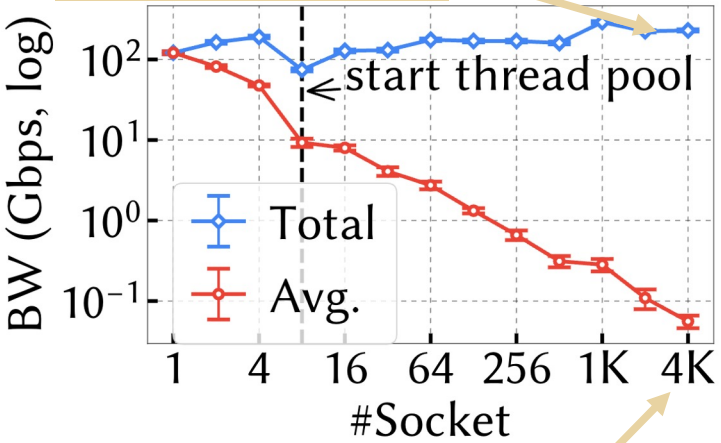

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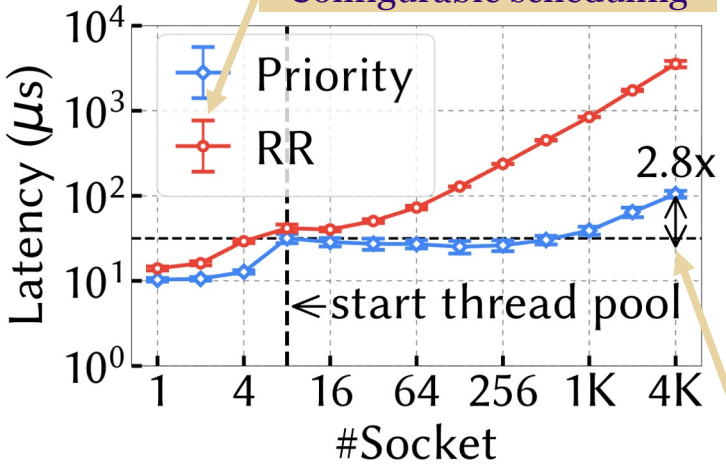

Strong isolation; for comparison, 128 SR-IOV VFs yield 3.7×

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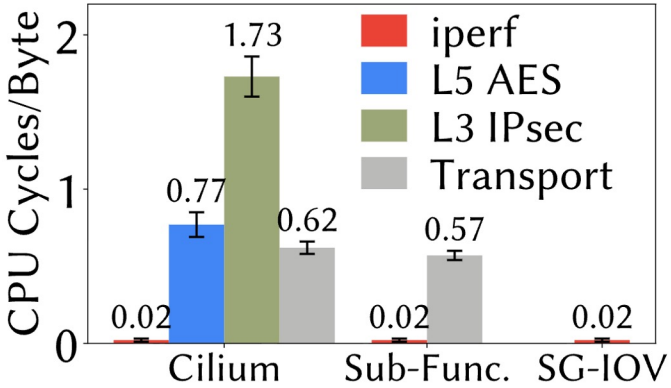

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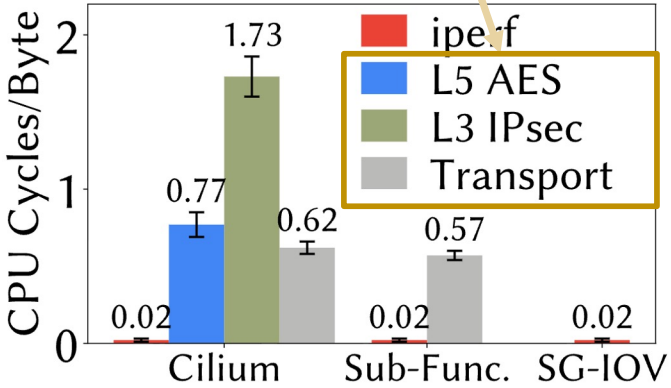
SG-IOV offloads these onto SmartNICs



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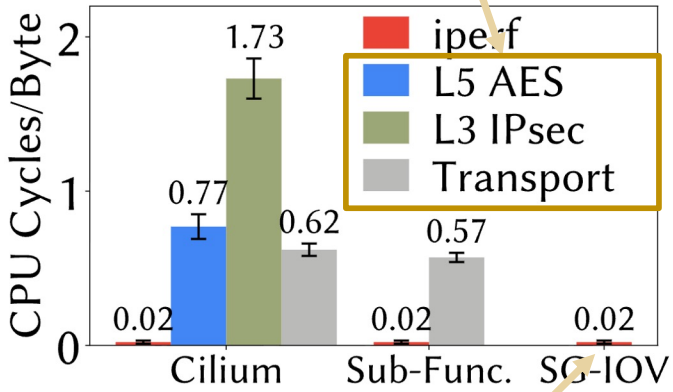

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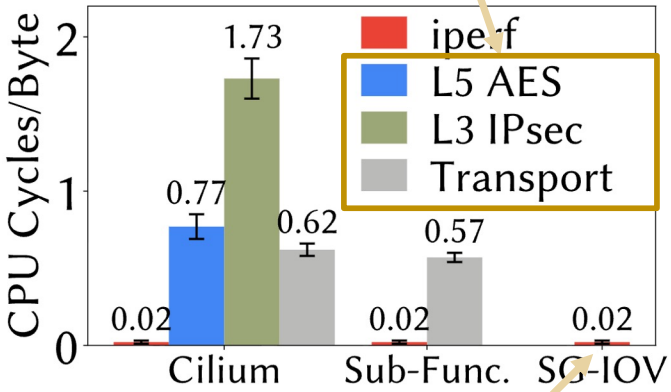

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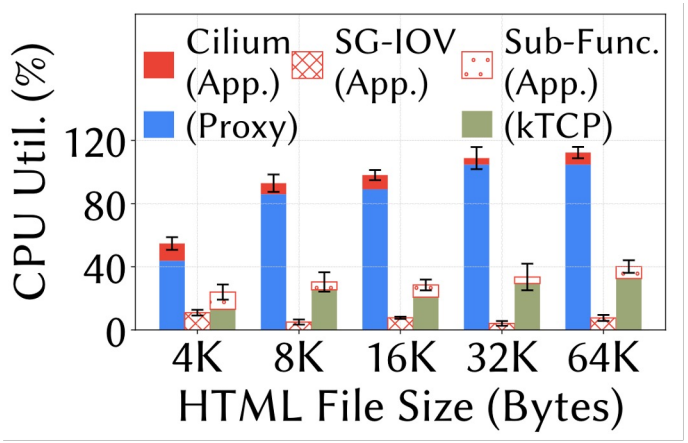

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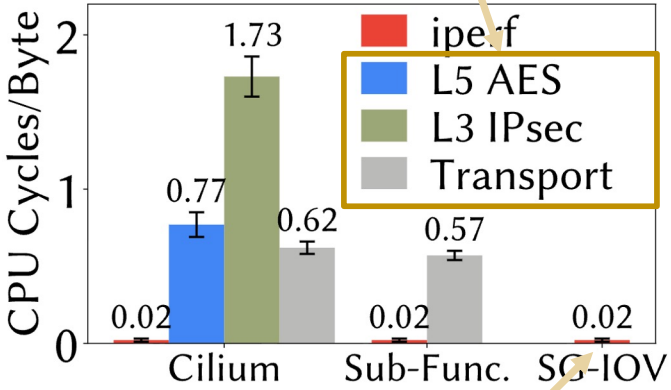

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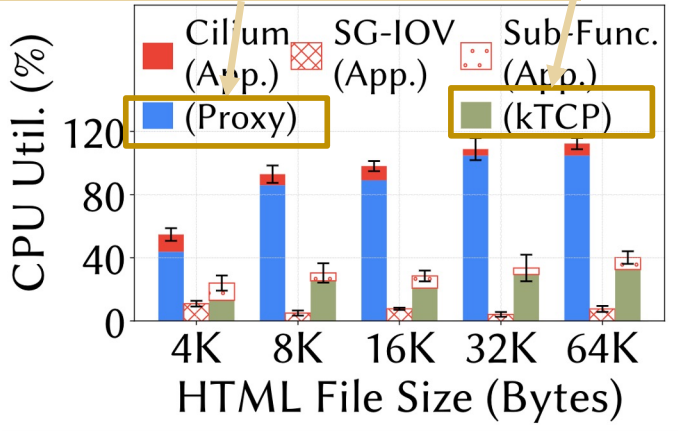

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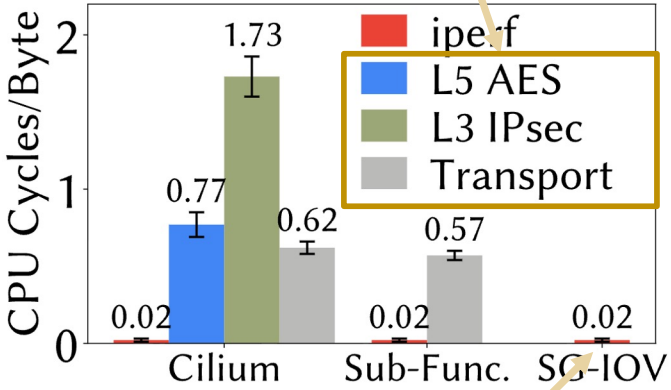

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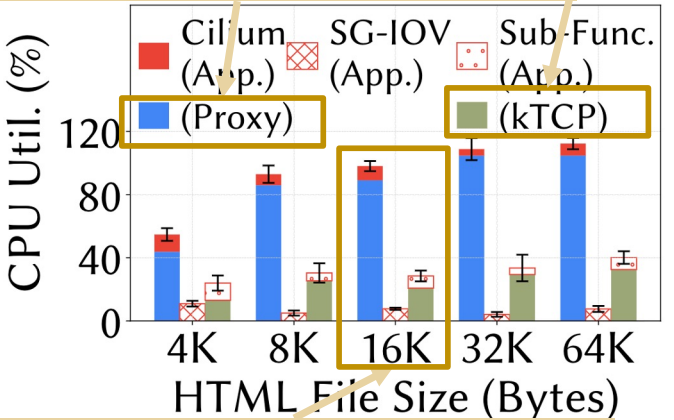

Save 1.06 CPU cores per connection

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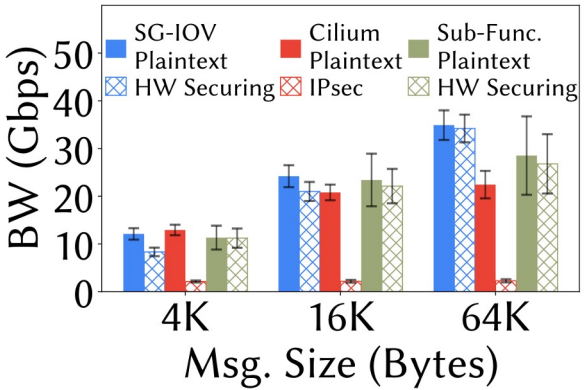

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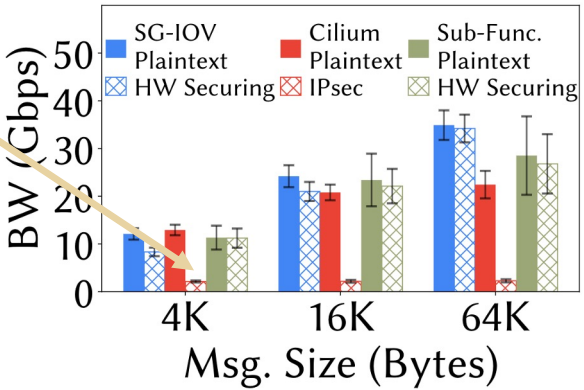

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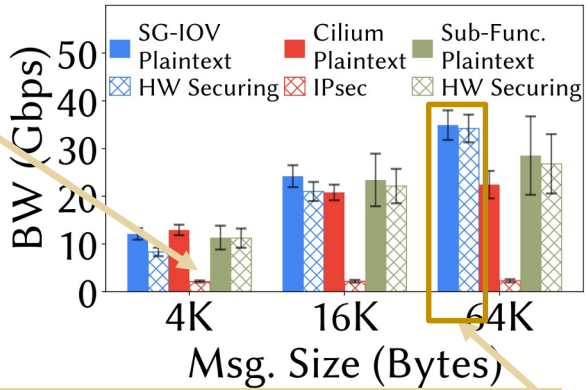

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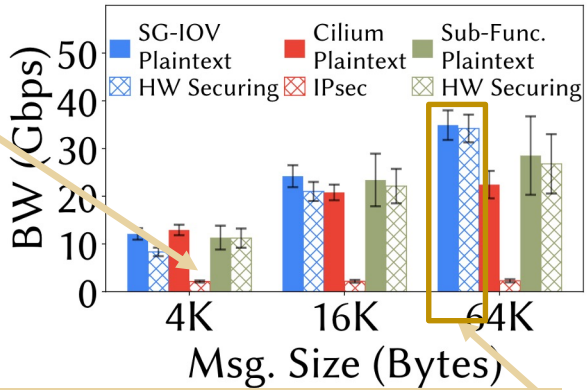

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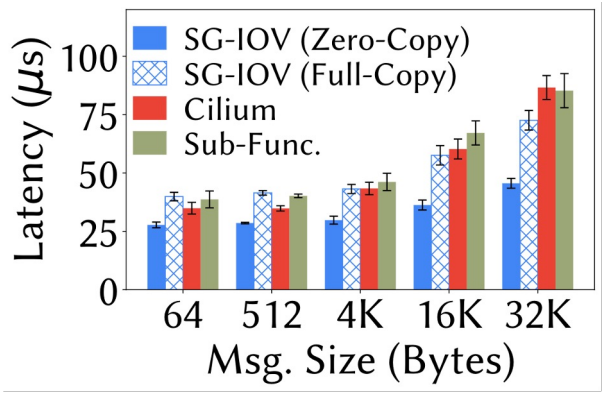

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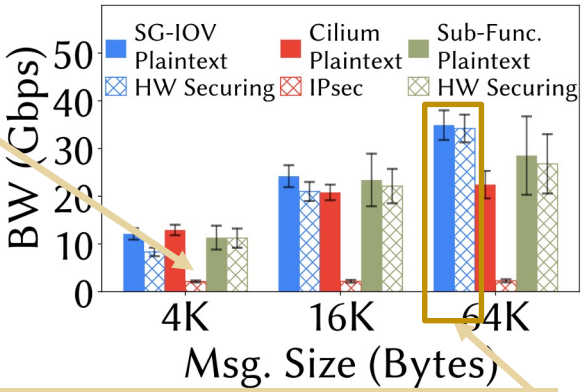

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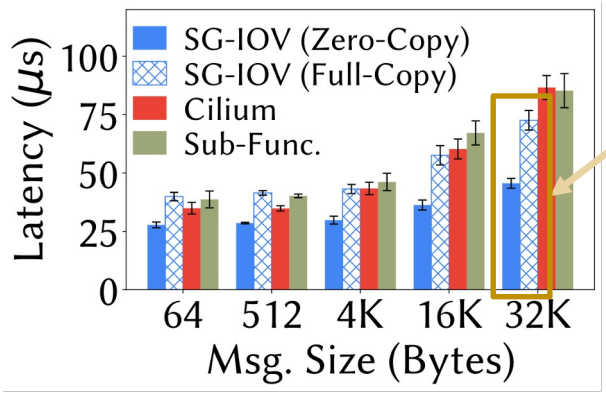

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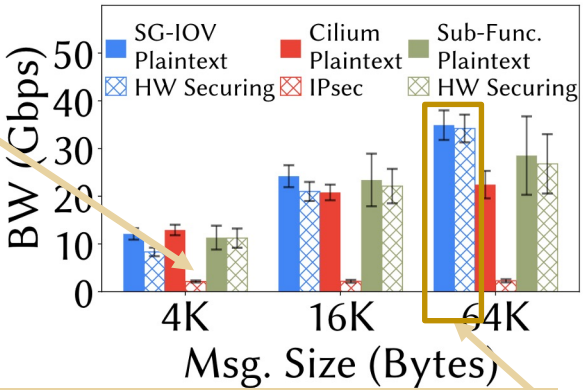

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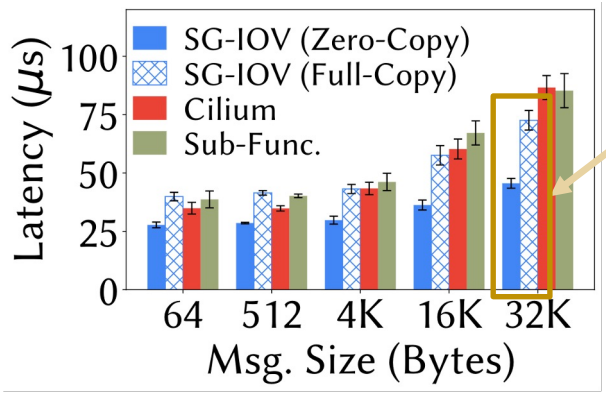

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See the paper for more results on functionality, scalability, and cost

Conclusion

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  - Flexibility
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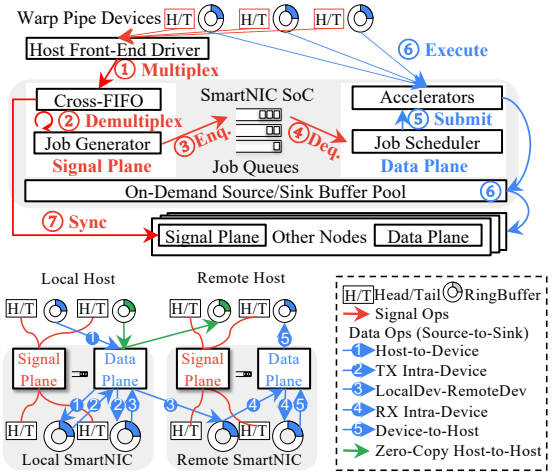

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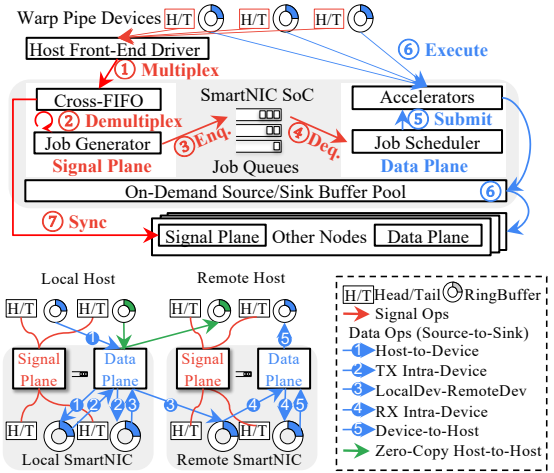

SG-IOV: Lifting Hardware IOV to Operate at L5 Socket Granularity

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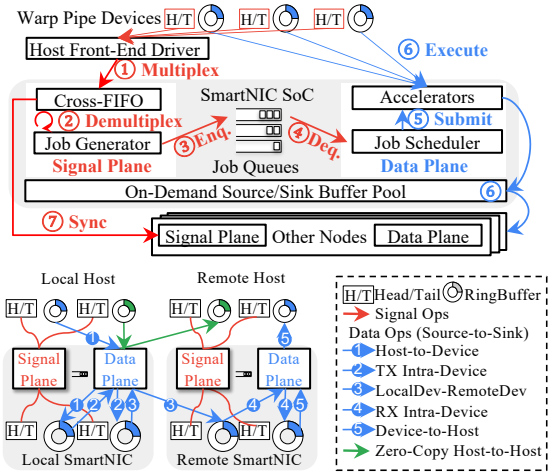

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ASPLOS

Thanks for listening!

Frank Chenxingyu Zhao
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