ZOC: Elastic and Cost-Efficient Virtual SmartNIC Architecture for Cloud Physical Machines

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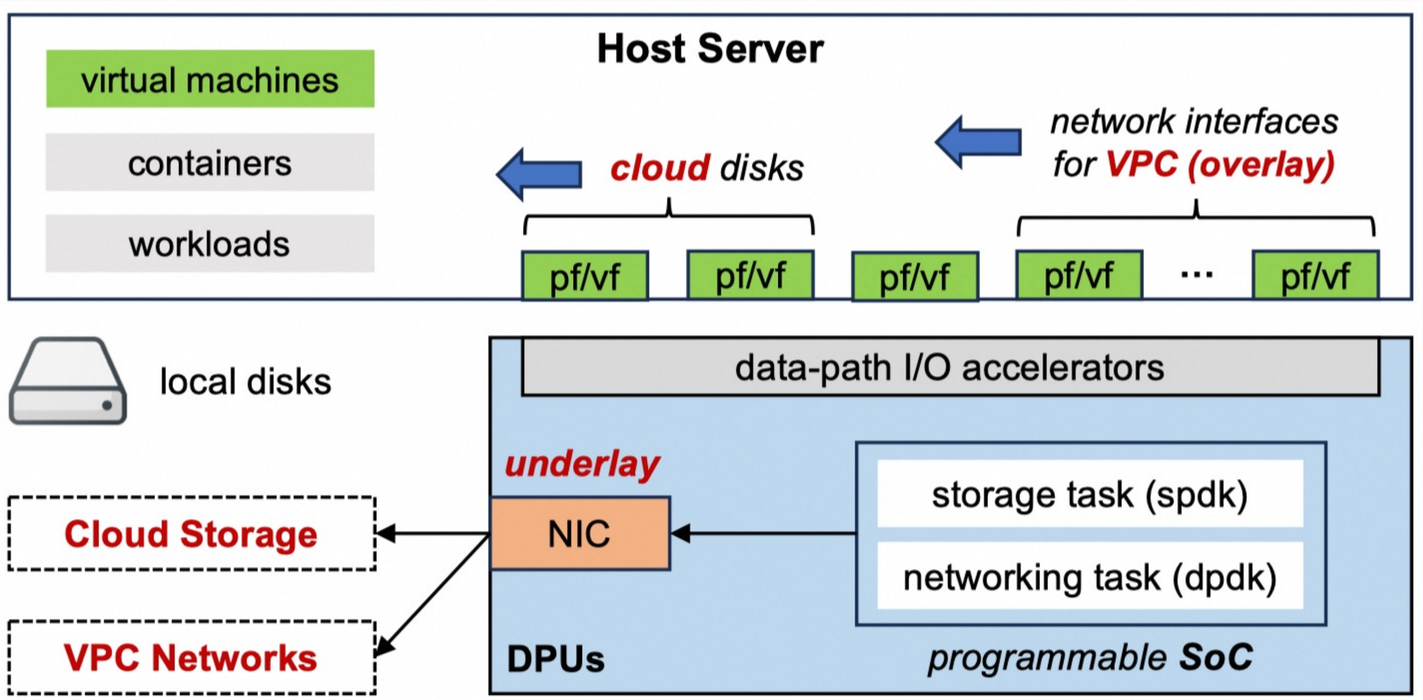
Background – From basic NIC to DPU

- **SmartNICs** extend basic NICs by integrating specialized or programmable processing units
- Data processing units (**DPUs**)—SmartNICs integrating a System-on-Chip (**SoC**)—have become central to modern cloud infrastructure



DPU-based cloud physical machine

- device model (PF/VF)
- classic VM support
- new model: bare-metal host

Motivation – DPU Challenges in Production

Heterogeneous Fleets (operational inconsistency)

- Legacy servers with only basic NICs; retrofitting with DPUs is costly
- Customer-owned infrastructure in private clouds: **> 50% new nodes lack DPU**

Limited Elasticity

- DPUs have fixed CPU/DRAM/accelerators, while cloud workloads exhibit dynamic I/O demands.
- Provisioned for peak loads to meet SLOs: **< 33% DPU utilization for > 99% of time**

Slow-Path Bottleneck

- Fast-path traffic (on data-plane accelerators) vs. Slow-path operations (e.g., state transitions and RPCs) on general-purpose subsystem (**constrained and precious**)
- Sustained slow-path traffic could saturate the general-purpose CPU/memory capacity.

Opportunities

Limitations of Existing Approaches

Most prior work on SmartNICs

Focuses on what to offload and how to optimize offload efficiency

vDUSE (userspace vDPA device)

Implements a software-defined data path to expose virtio devices to the host server (no NVMe support)

Tight OS coupling: Shared kernel for IaaS & PaaS leads to conflicts on versioning, networking, and maintenance

Key Opportunities

Service VM

Decouple infrastructure from host OS with guest cooperation & para-virtualization

Elastic Host Resources

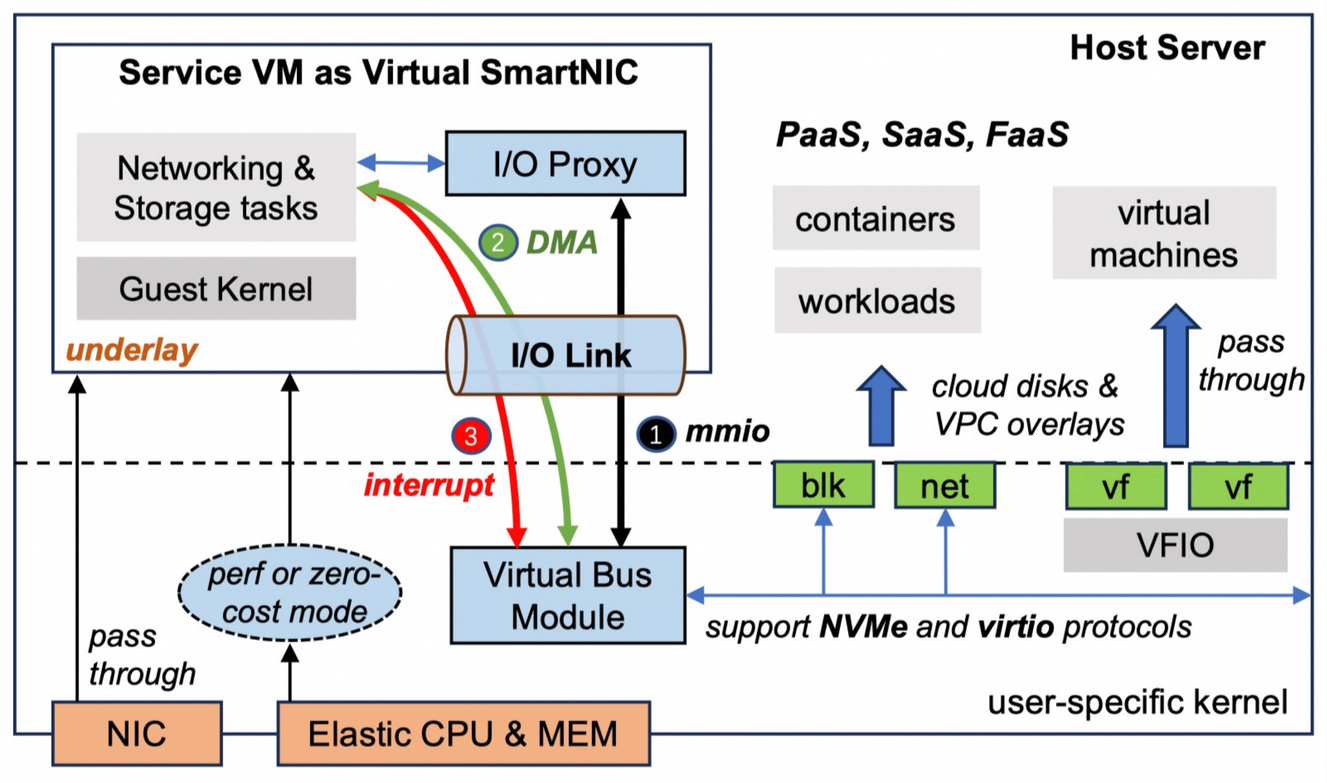
Servers have hundreds of cores & TBs of DRAM; turbo freq far exceeds DPU SoCs

Idle Resource Harvesting

Cloud CPUs are widely underutilized; opportunistic vCPU scheduling to utilize otherwise-idle CPU resources

How to project high-level device abstraction from the service VM to the host

ZOC Architecture – Software-Defined Virtual SmartNIC



A production-ready complement (with only basic NICs) to existing DPU-based architecture

Key Insight

Combine a passthrough NIC with dynamically provisioned host resources in a dedicated **Service VM** to form a virtual SmartNIC.

Three Components

I/O Proxy (Service VM)
Device & protocol emulation (virtio / NVMe)

Virtual Bus (Host)
Exposes standardized I/O device interfaces

I/O Link (Bridge)
MMIO, DMA transfer, interrupt delivery

Service VM Design

Operational Consistency

- Dedicated OS, fully decoupled from host; the passthrough NIC enables transparency.
- Reuse existing DPU infrastructure components; Consistent user experience for cloud workloads

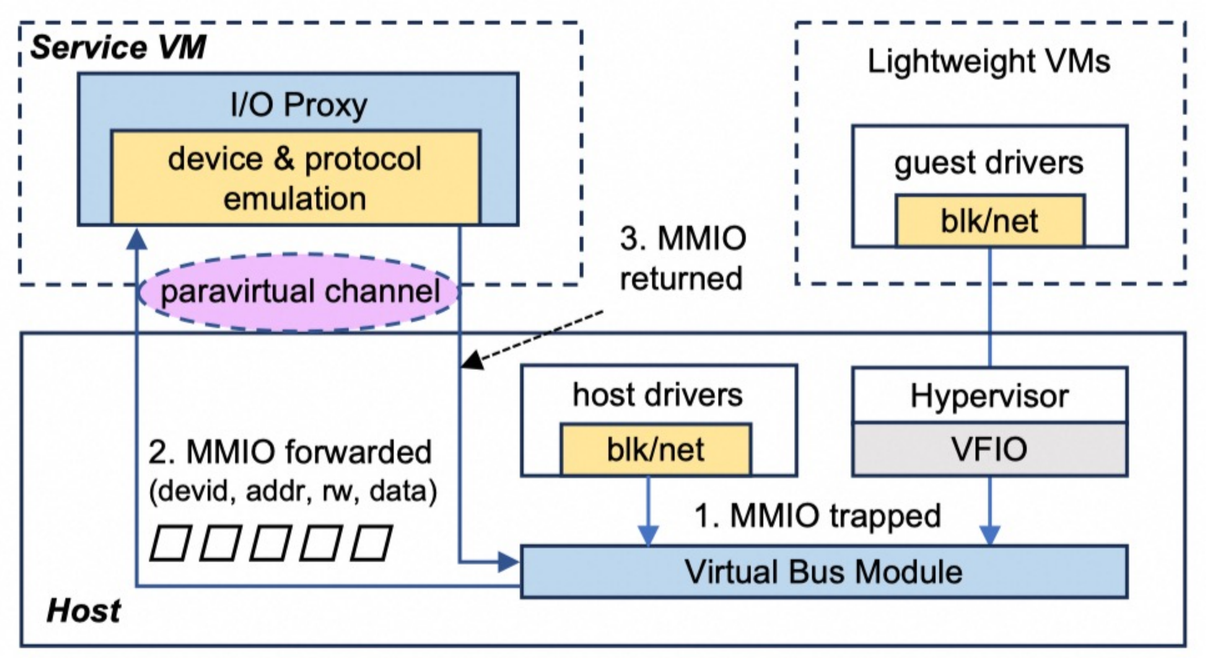
Resource Elasticity

- Elastically configured—from lightweight instances (e.g., 2c/8g) to scaled-up setups (e.g., 16c/64g)
- Runtime hot-plug of CPU or memory for dynamic I/O patterns

Two running modes

- Performance: dedicated CPU cores via vCPU pinning
- Zero-cost: harvest idle cycles from co-located workloads (controlled interference)

Cross-Domain MMIO for Device Abstraction



MMIO Workflow (Trap-and-Emulate)

1. **MMIO Trapped**
   Host/guest driver issues MMIO to Virtual Bus

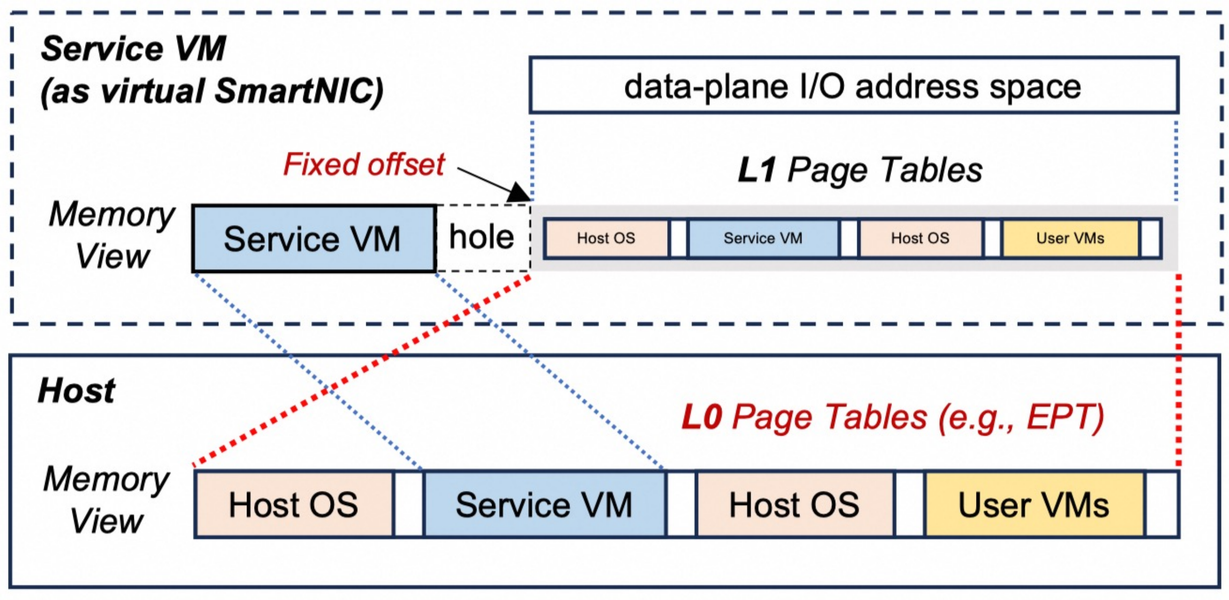
2. **MMIO Forwarded**
   Encapsulated & sent to I/O Proxy via paravirtual channel (devid, addr, rw, data)

3. **MMIO Returned**
   I/O Proxy emulates device register semantics, returns result through same path

Devices can be either probed by **native host drivers** or claimed via **VFIO** for guest passthrough

DMA Transfers & Interrupt Delivery

DMA via 2D Page Tables (Hardware-accelerated)



- L0 page tables map entire **HPA** into Service VM's **GPA** with fixed offset (fast calculation)
- L1 page tables map **GPA** to userpace **IOVA**
- Address space management: shared by devices for the same domain, isolated across domains (host, user VMs)

Efficient Interrupt Delivery

Basic
VM hypercall to forward interrupts (VM Exit overhead)

Optimized
Map **physical ICR** into Service VM; cross-domain IPI to forward interrupts (without VM Exit)

For user VMs
Map virtual interrupt controller; use Posted Interrupt for zero-exit delivery

Experimental Setup & Cost Model

ZOC Testbed

- 2x Intel Xeon 8369B (128 cores, 3.5GHz turbo), 1TB DRAM
- Mellanox ConnectX-5 as Basic NIC
- Linux kernel 5.10, varied Service VM configs

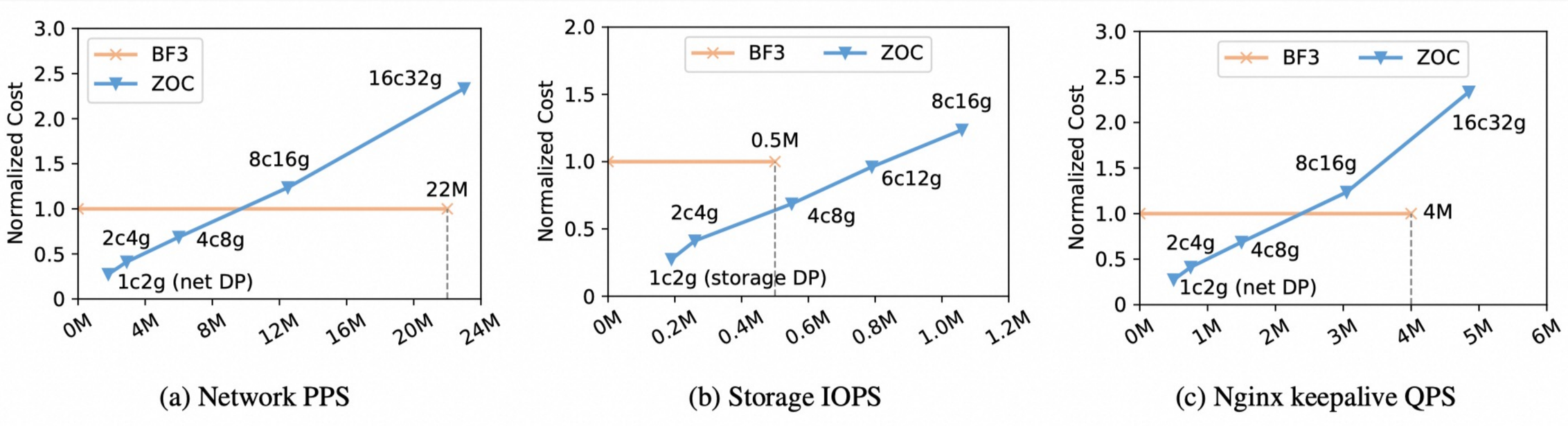
Comparison: BlueField-3 P-Series DPU (BF3)

- 16 ARM Cortex-A78AE cores, 32GB DRAM
- ConnectX-7 (dual-port 200GbE) NIC inside
- DOCA SDK utilized to maximize hardware capabilities

Incremental Hardware Cost

- BF3: ~$1,500 (estimated based on incremental retail price plus an adjustment factor)
- ZOC: $95 per logical core and $4 per gigabyte, **scales linearly** with the amount of CPU and memory resources allocated to the service VM

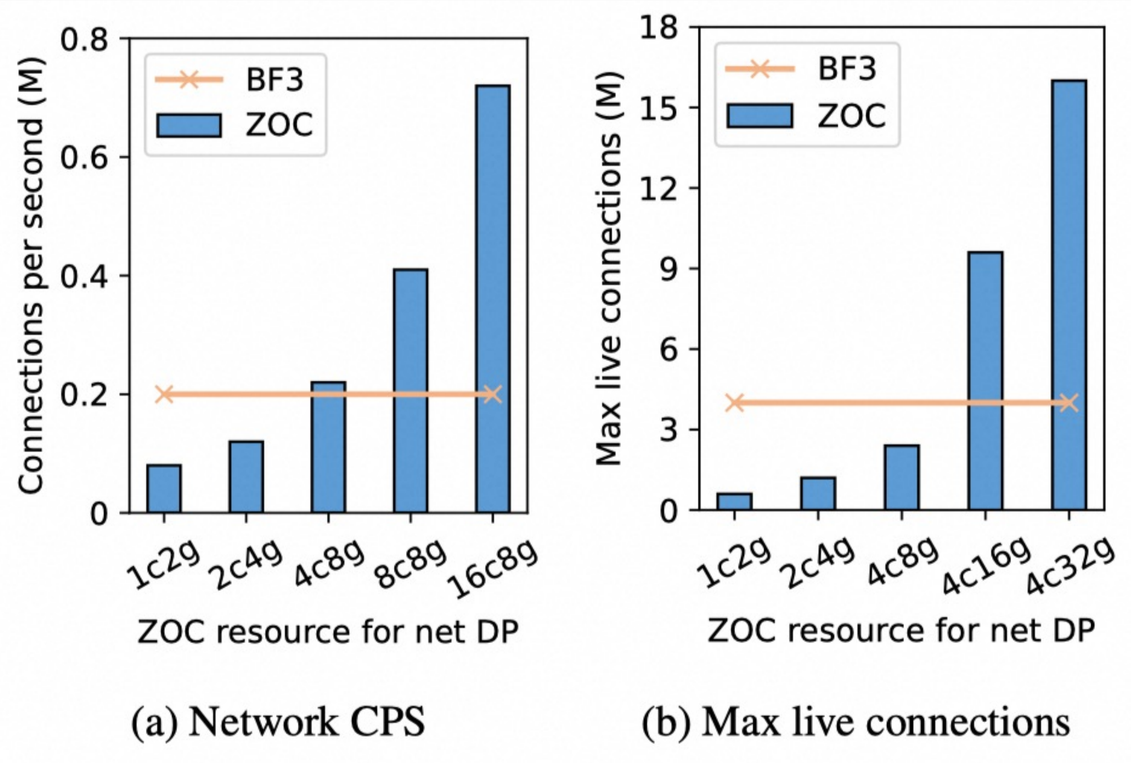
Cost Efficiency and Performance Scalability



BF3 has a fixed cost; ZOC has scalable performance and lower cost for low-to-moderate I/O demands

- Networking: 4c8g provides 6M PPS at 69% of BF3 cost, sufficient for diverse cloud services
- Storage: 8c16g delivers over 1M IOPS, more than doubling BF3’s peak performance

Slow-Path Processing



Connections per second (cpu-intensive)

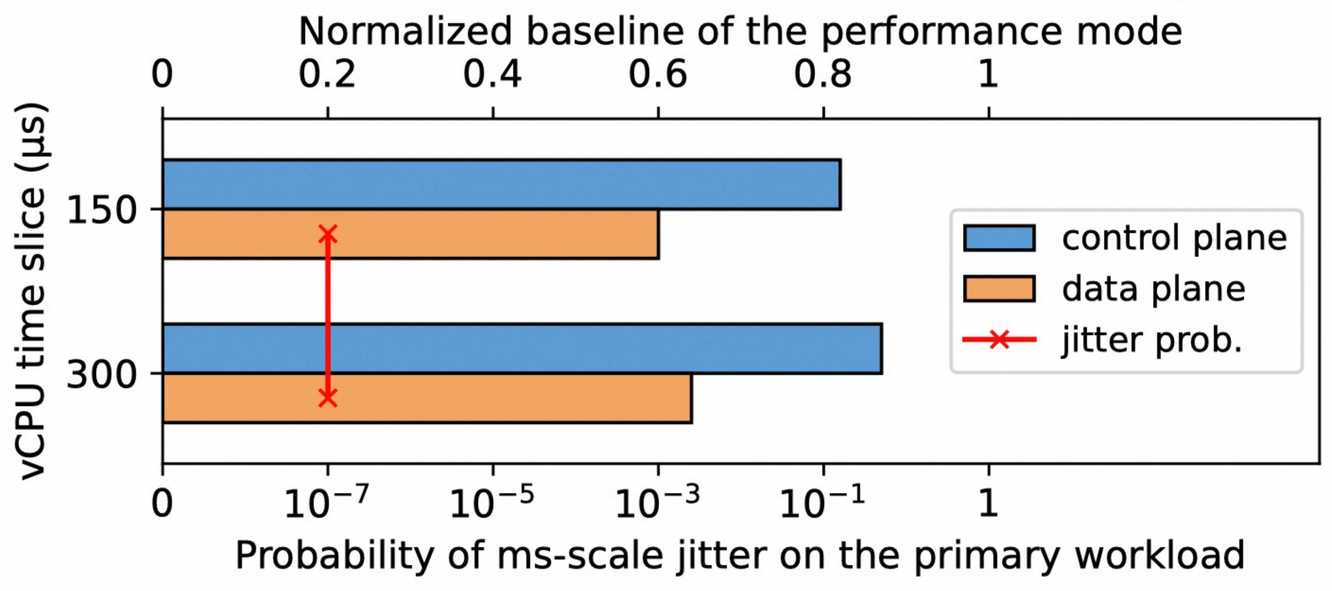
- 16c8g to deliver 0.72M CPS - 3.6x improvement over BF3 (0.2M)
- Near-linear scaling with host resources

Max Sessions (memory-intensive)

- 4c32g to deliver 16M sessions - 4x BF3 (4M)
- Fine-grained CPU-to-memory ratio tuning

Zero-Cost Mode

Question: In worst-case scenarios (no idle CPU cycles), what is ZOC's I/O throughput and the resulting interference?



Key Design

- Fine-grained vCPU time slice (150µs)
- Round-robin preemption across busy cores to amortize interference

- ~82% of baseline for control plane; ~60% of baseline for data plane (cache thrashing)
- Strong tail latency guarantee for primary workload: < 10^-7 probability of ms-scale jitter

Compatibility & Maintainability

High Compatibility in the Real Cloud

- Reuse most existing DPU IaaS components inside the service VM (OS, agents, control planes)
- Cloud services maintain nearly identical runtime behavior on ZOC-based nodes
- Only a small virtualization overhead

High Maintainability

- DPU: FPGA/ASIC firmware may require cold reboot even for minor changes
- ZOC: designed from the ground up to support fine-grained updates across all components

Table 1: ZOC's virtualization overhead under extreme load

	Physical CPU	*ZOC vCPU*
Peak Network PPS	100%	98%
Peak Storage IOPS	100%	96.5%

Table 2: Hot updates of ZOC components

Components	*Service downtime*	*Scale with device counts*	*Influences*
Kernel parts	0	/	None
I/O Proxy	10+ ms	Yes	Control plane
Service VM	50 ms	No	Control & Data

Conclusion & Future Work

Key Contributions

1. Transform legacy servers at **no additional hardware cost**
2. Enable **unified software stacks** across DPU-based and DPU-less environments
3. Fine-grained **resource elasticity** + zero-cost mode harvesting idle cycles
4. Performance **scalability** to eliminate DPU slow-path bottlenecks

Future Directions

- ZOC + DPU synergistic cooperation for expanded I/O capacity
- Reclamation of idle CPU cycles & cold memory pages within Service VM
- CXL-connected rack-scale elasticity: remote I/O services & shared acceleration

Thank You!

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