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Edge-RT: OS Support for Controlled Latency in the Multi-Tenant, Real-Time Edge

Wenyuan Shao, Bite Ye, Huachuan Wang, Gabriel Parmer and Yuxin Ren
{shaowy, bitye, hcwang, gparmer, ryx}@gwu.edu

Interacting with the Cloud

Main purpose of interacting with cloud:

1. Offload computations to the cloud.
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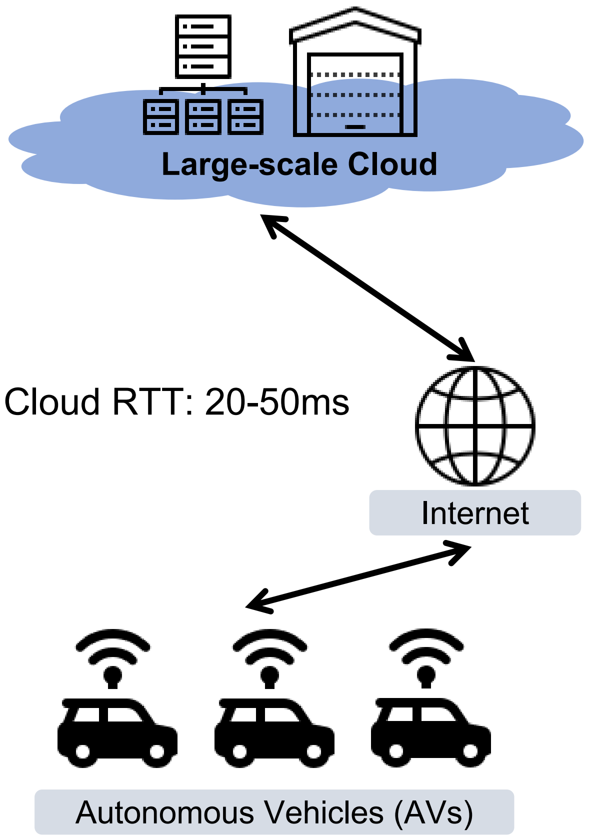

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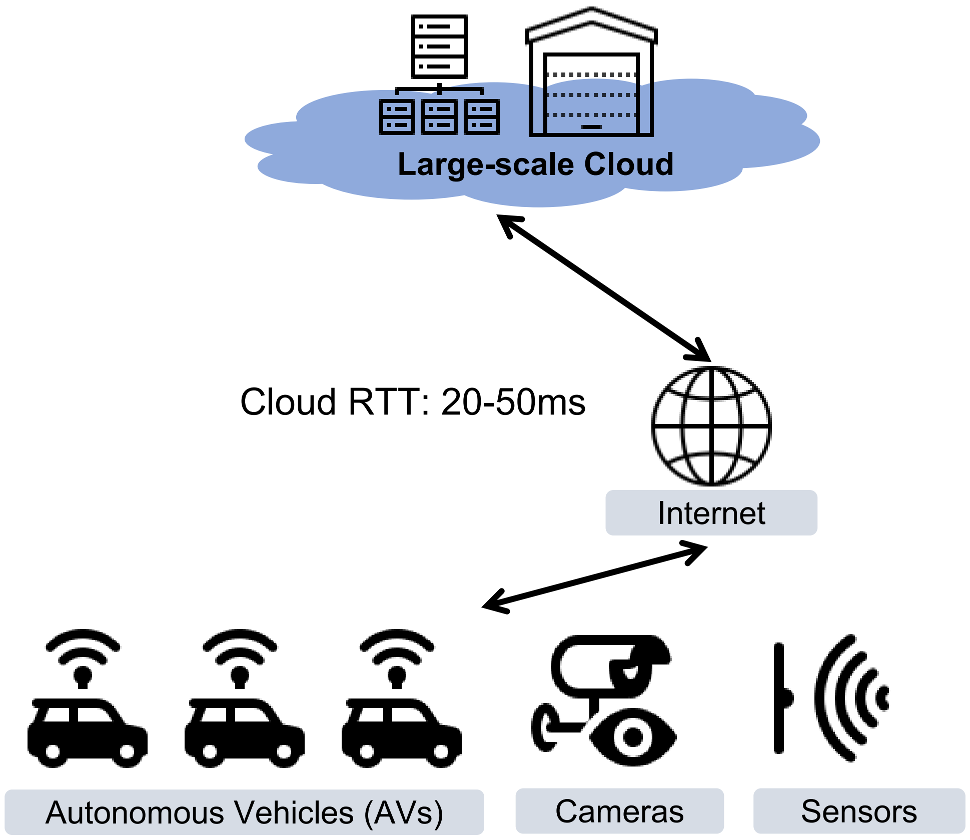

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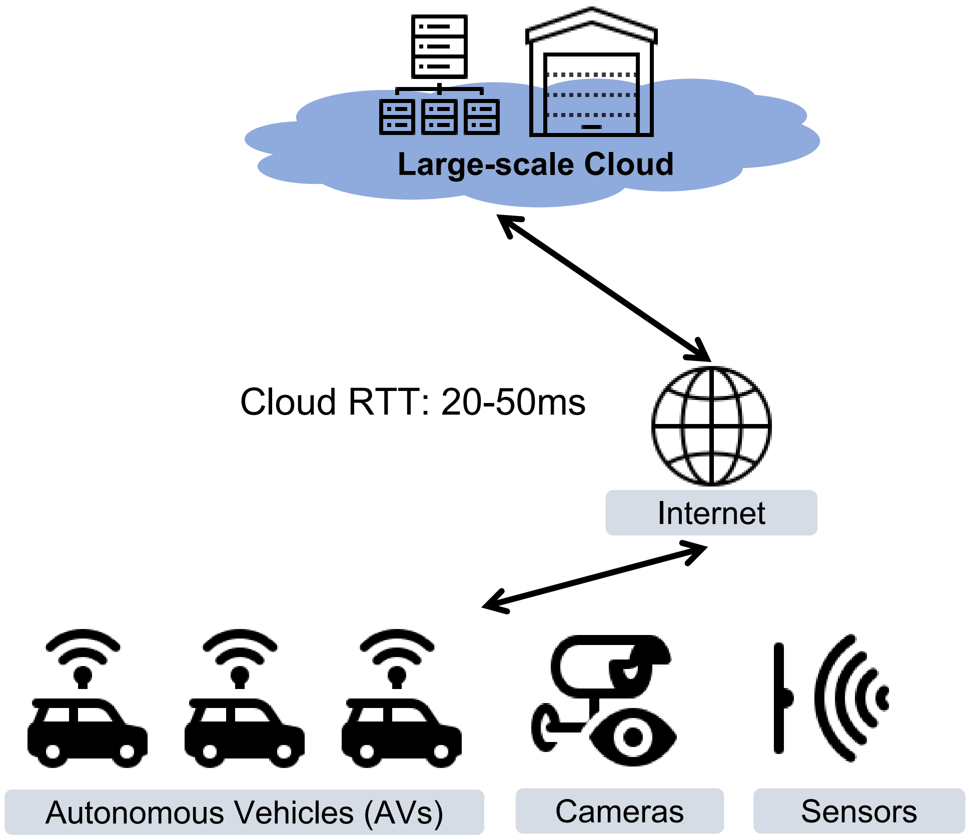
For both examples, multiple clients require real-time responses from the cloud.



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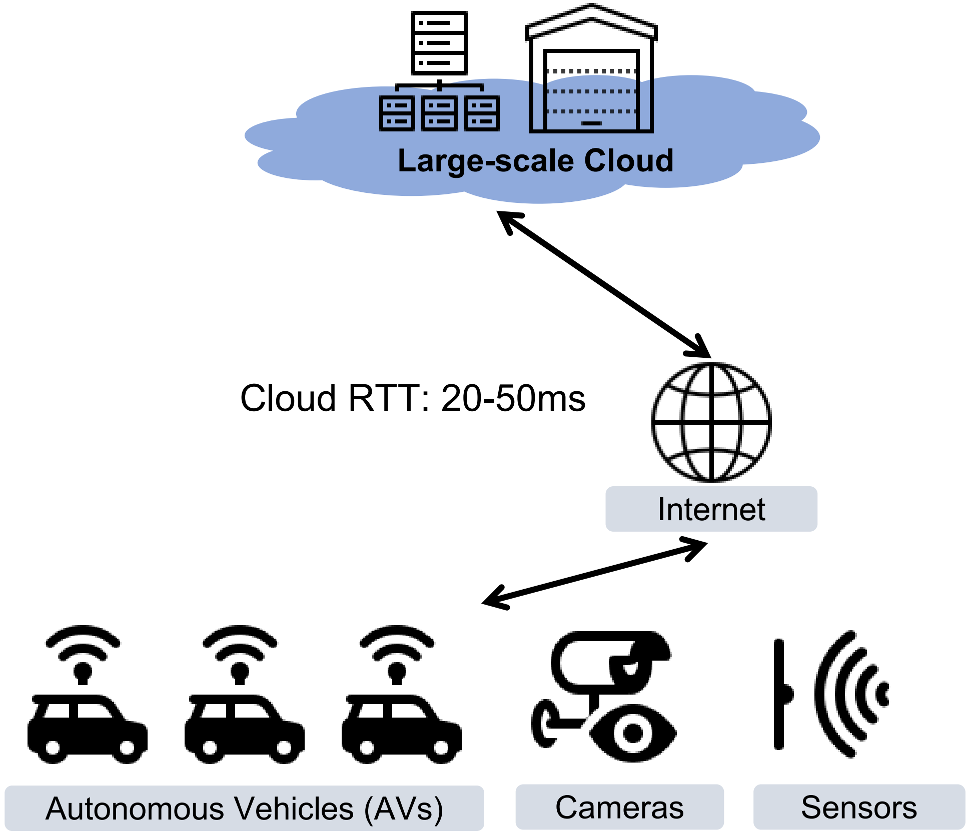

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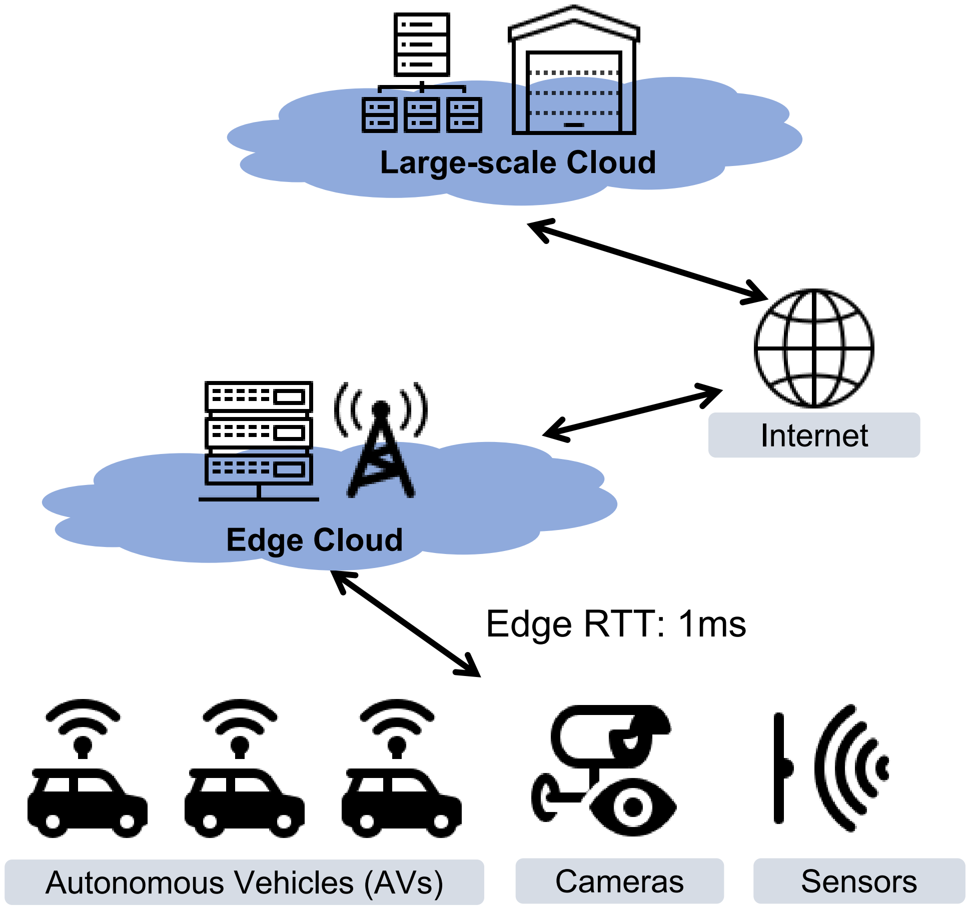

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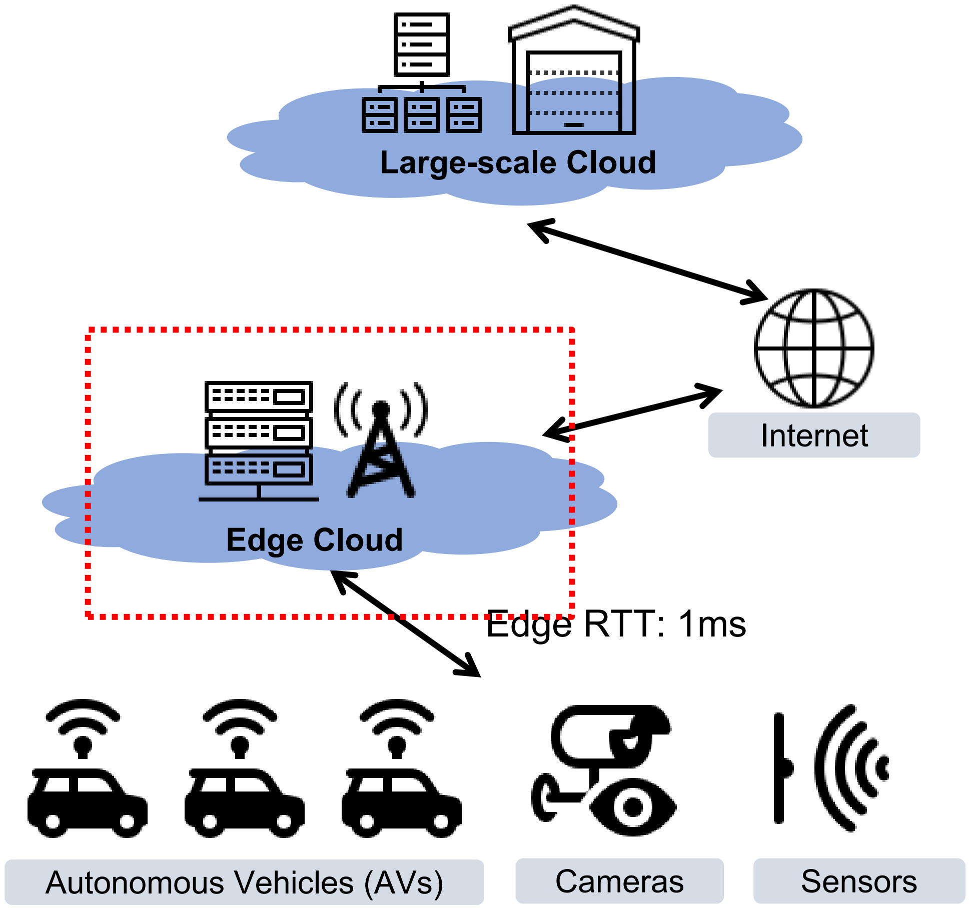

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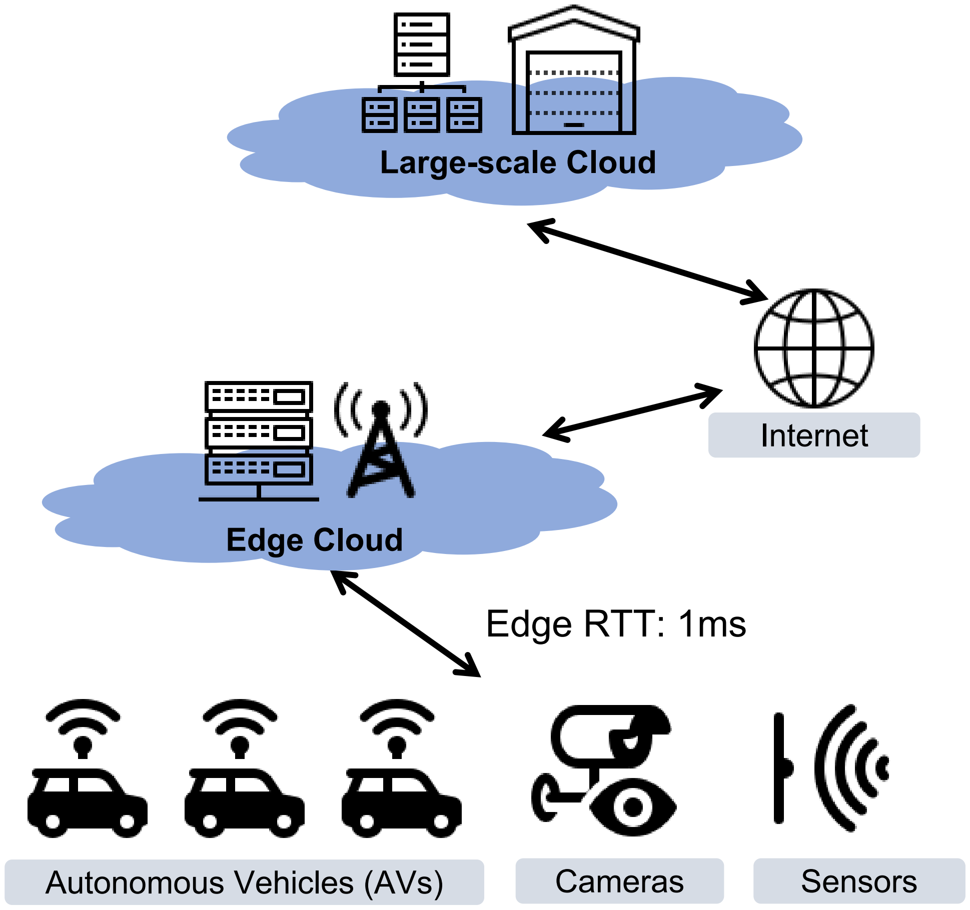

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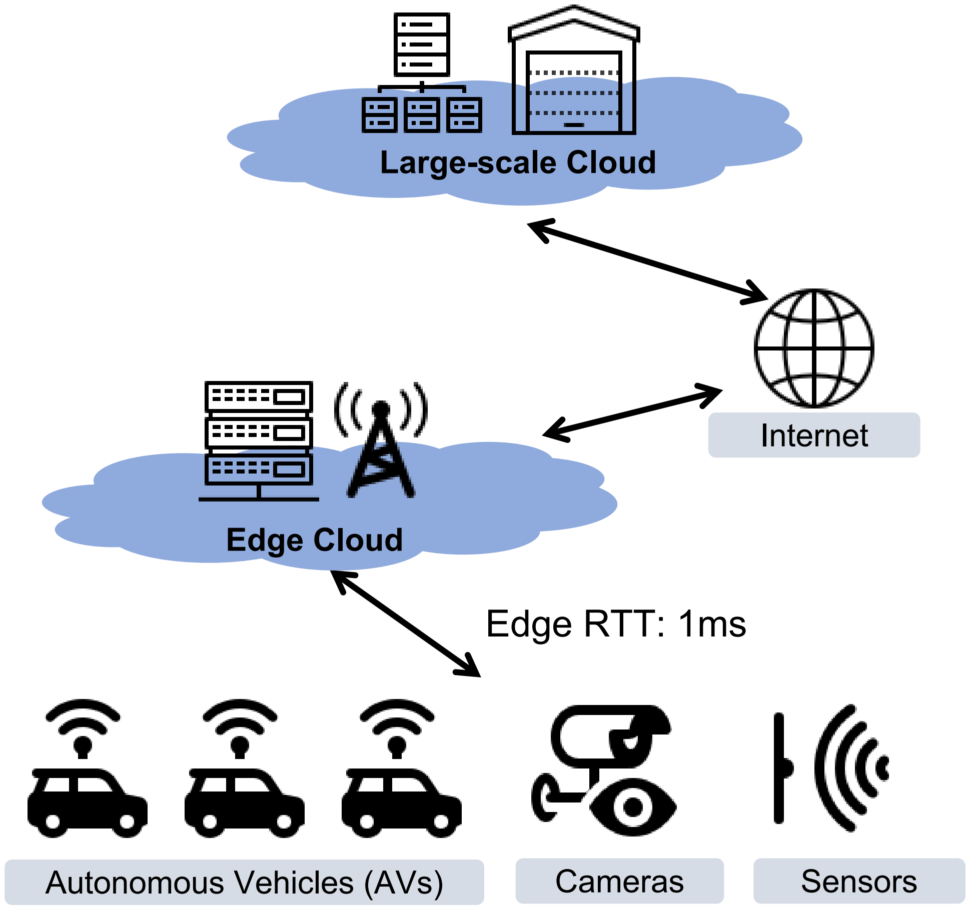

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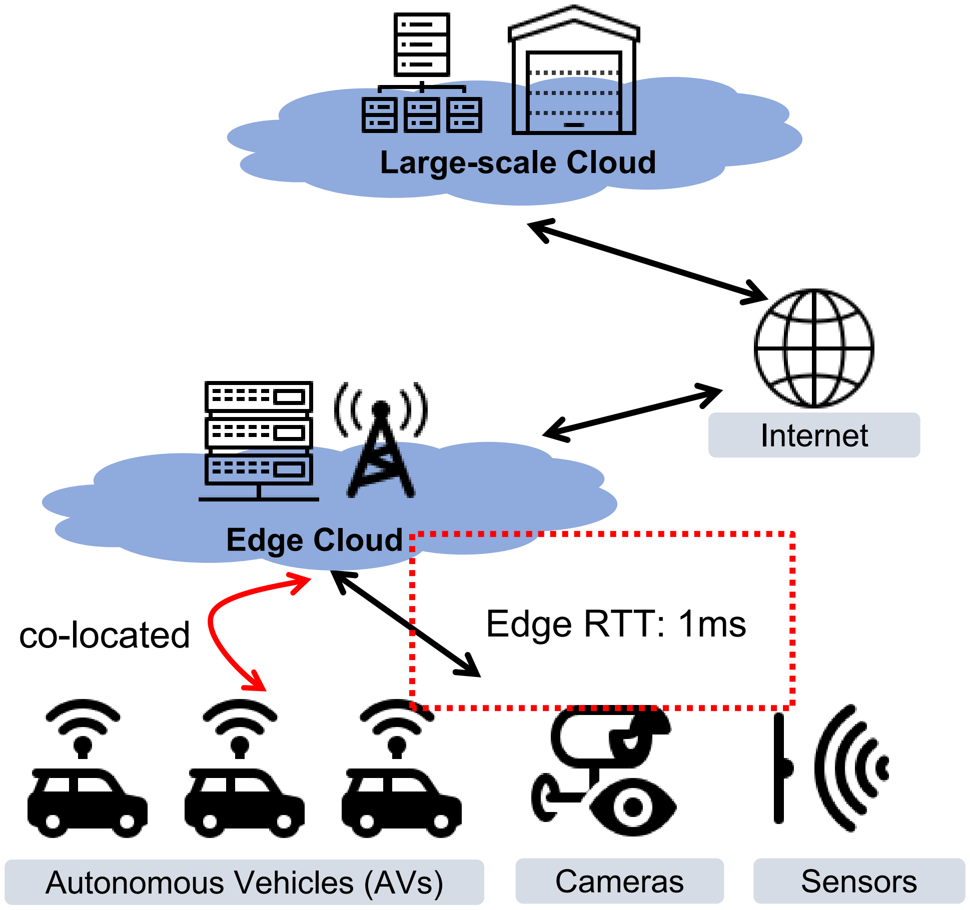

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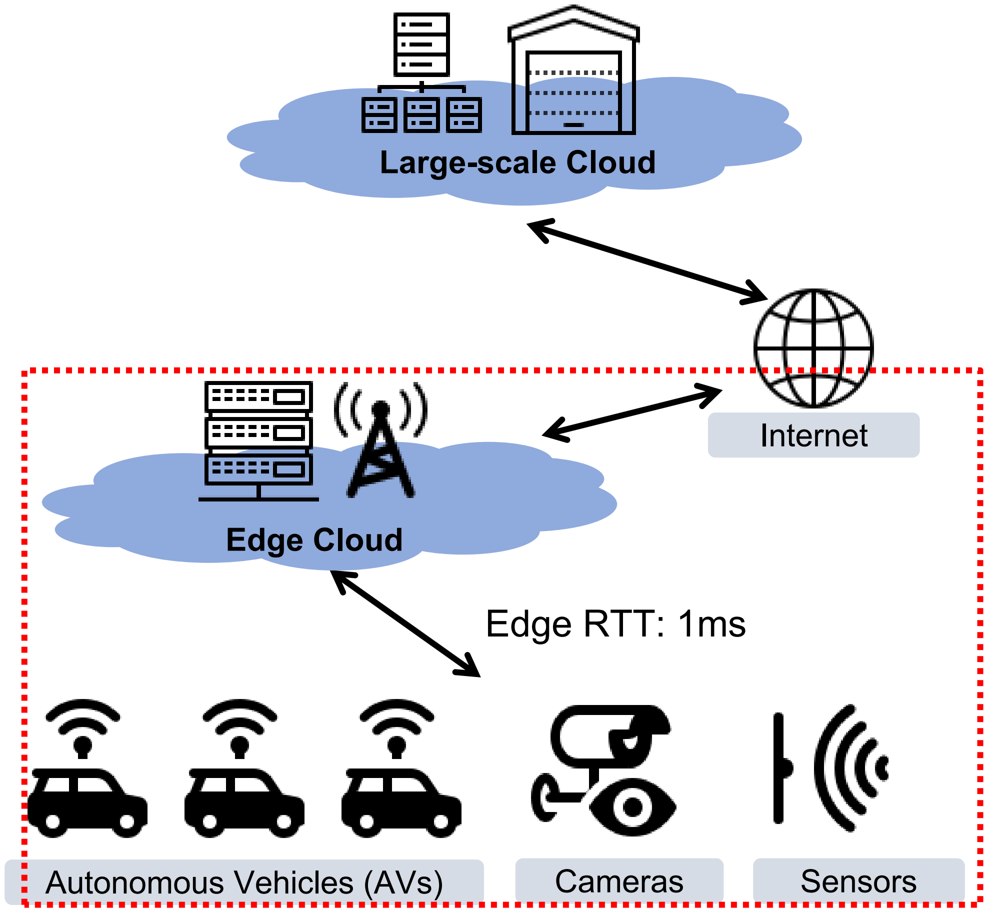

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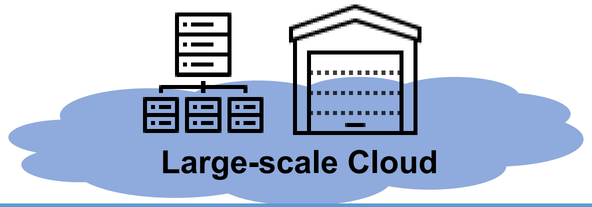

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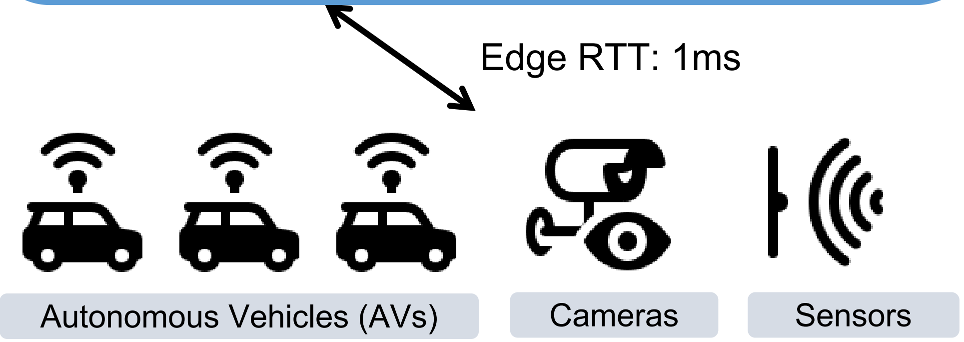
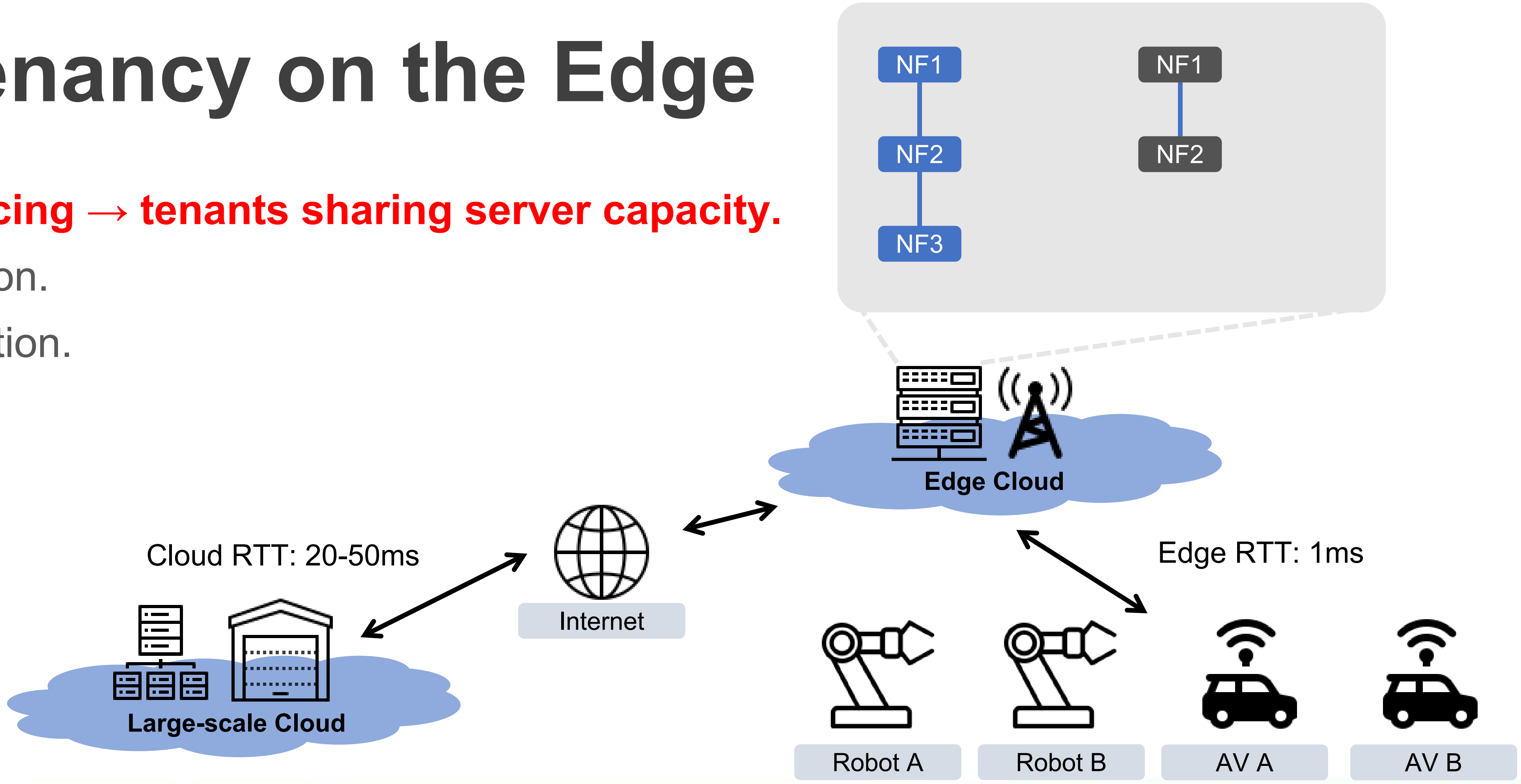
1. **Multi-tenancy.**
2. High density dynamic workload.
3. Deadline-aware.



Multi-tenancy on the Edge

- **Network slicing → tenants sharing server capacity.**
- Client isolation.
- Tenant isolation.



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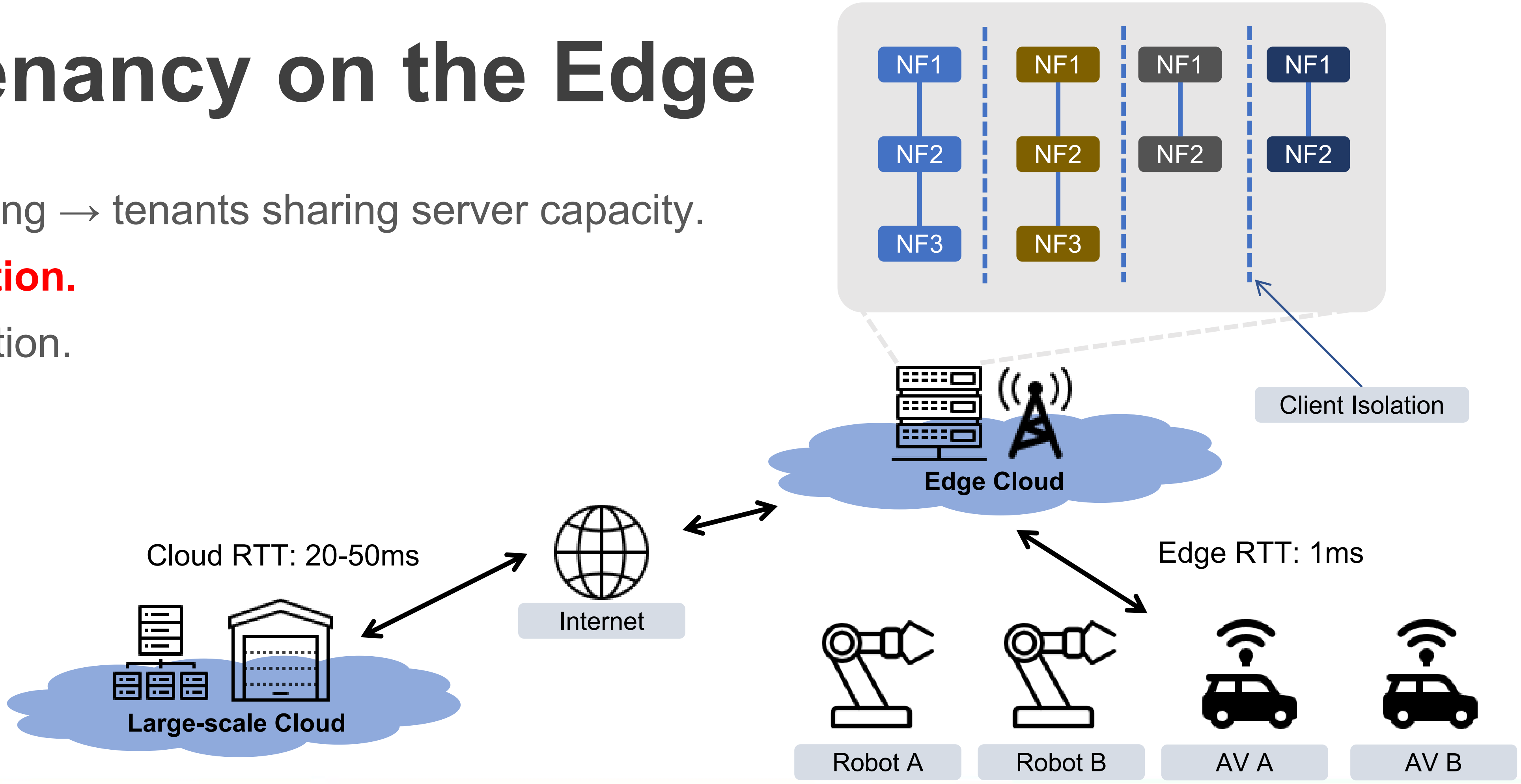

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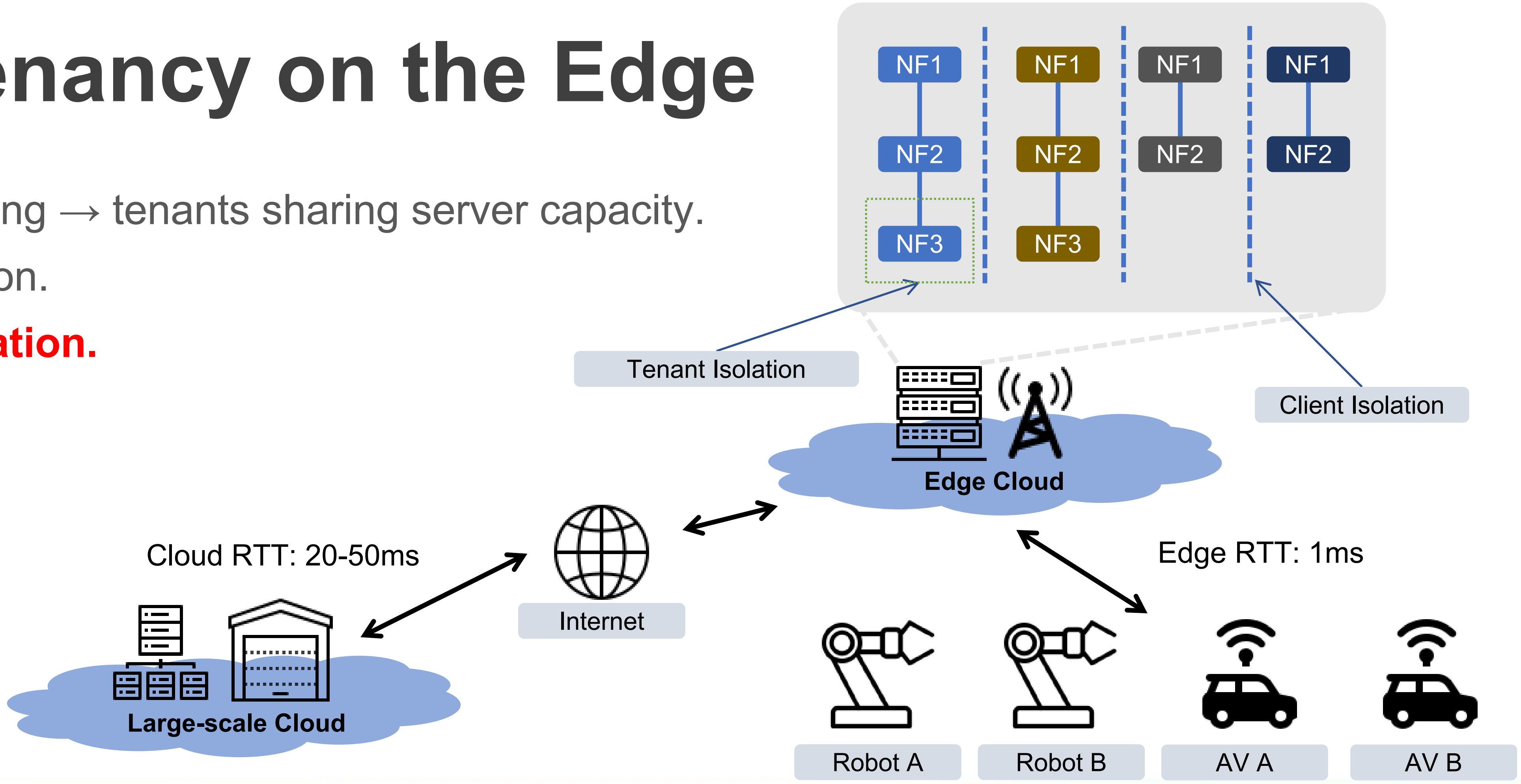

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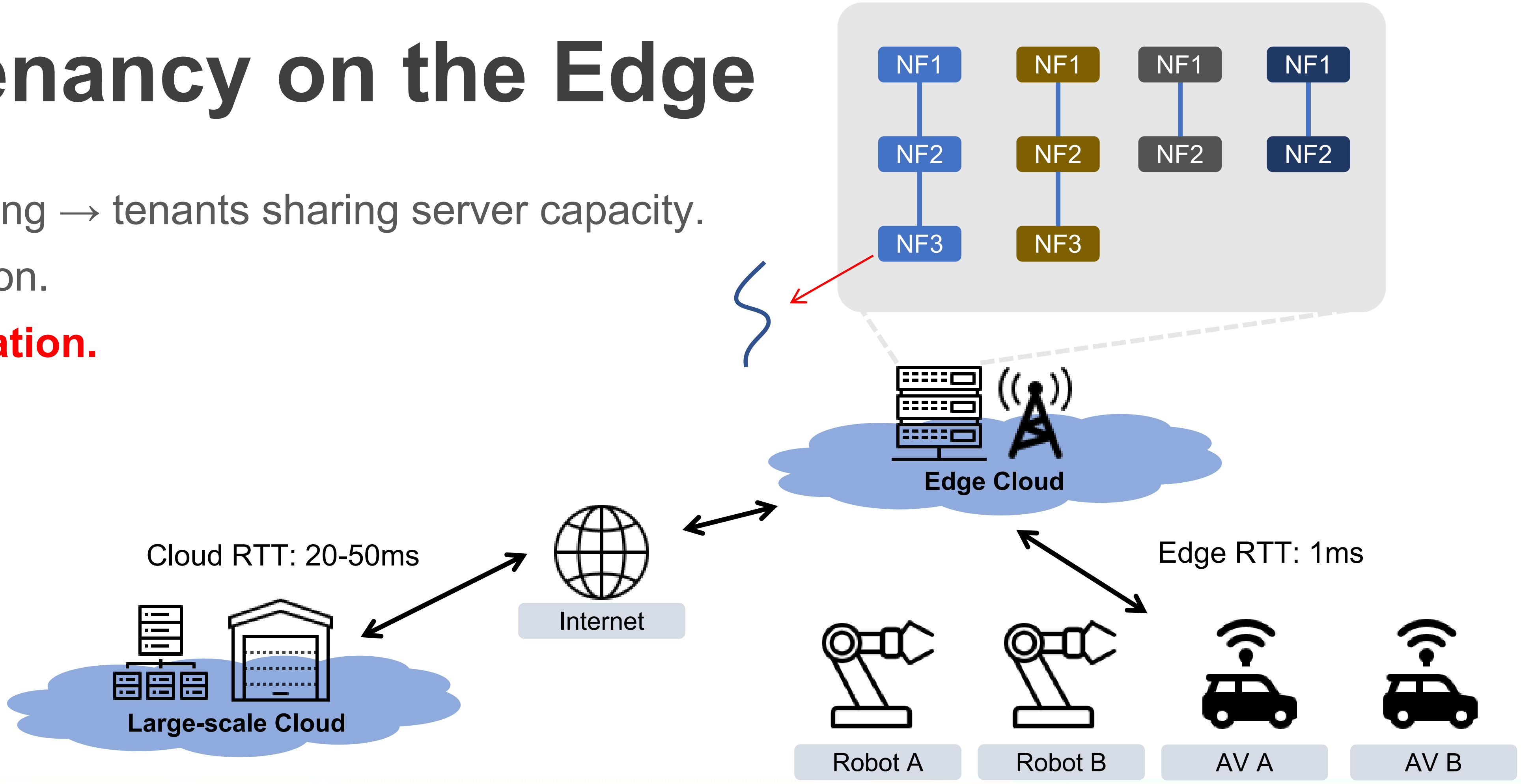

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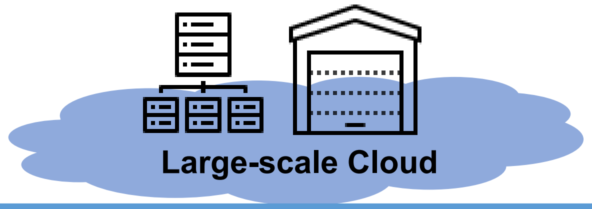

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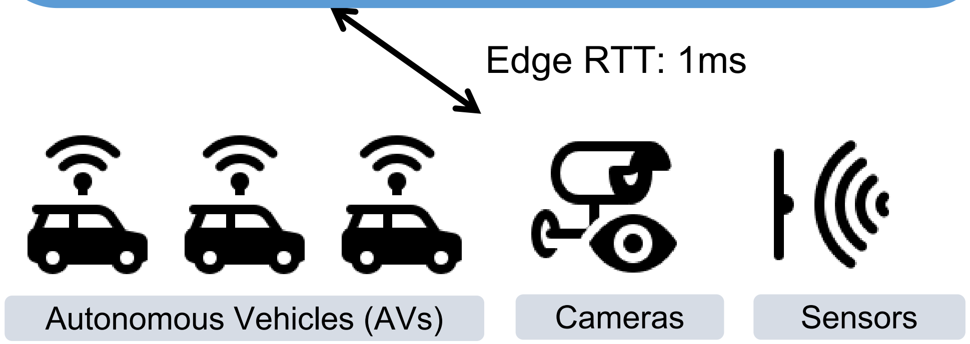

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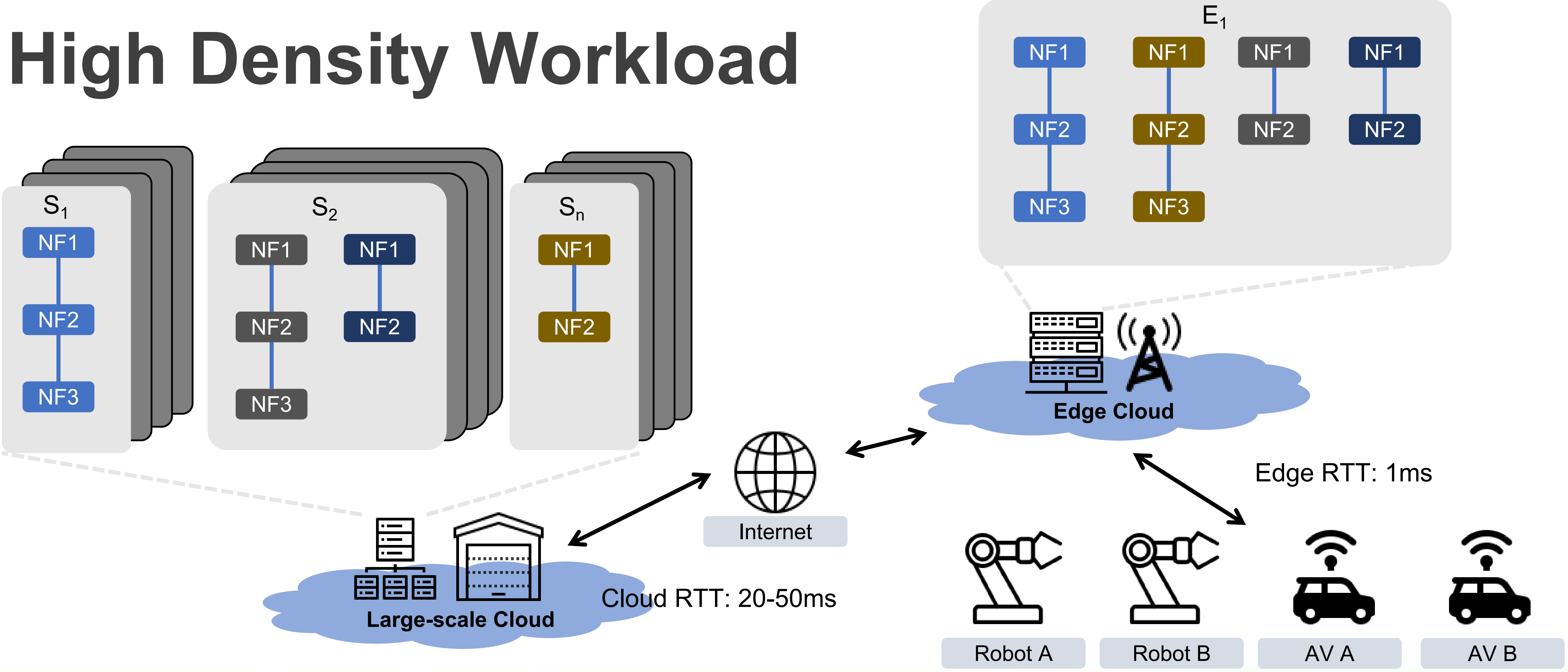
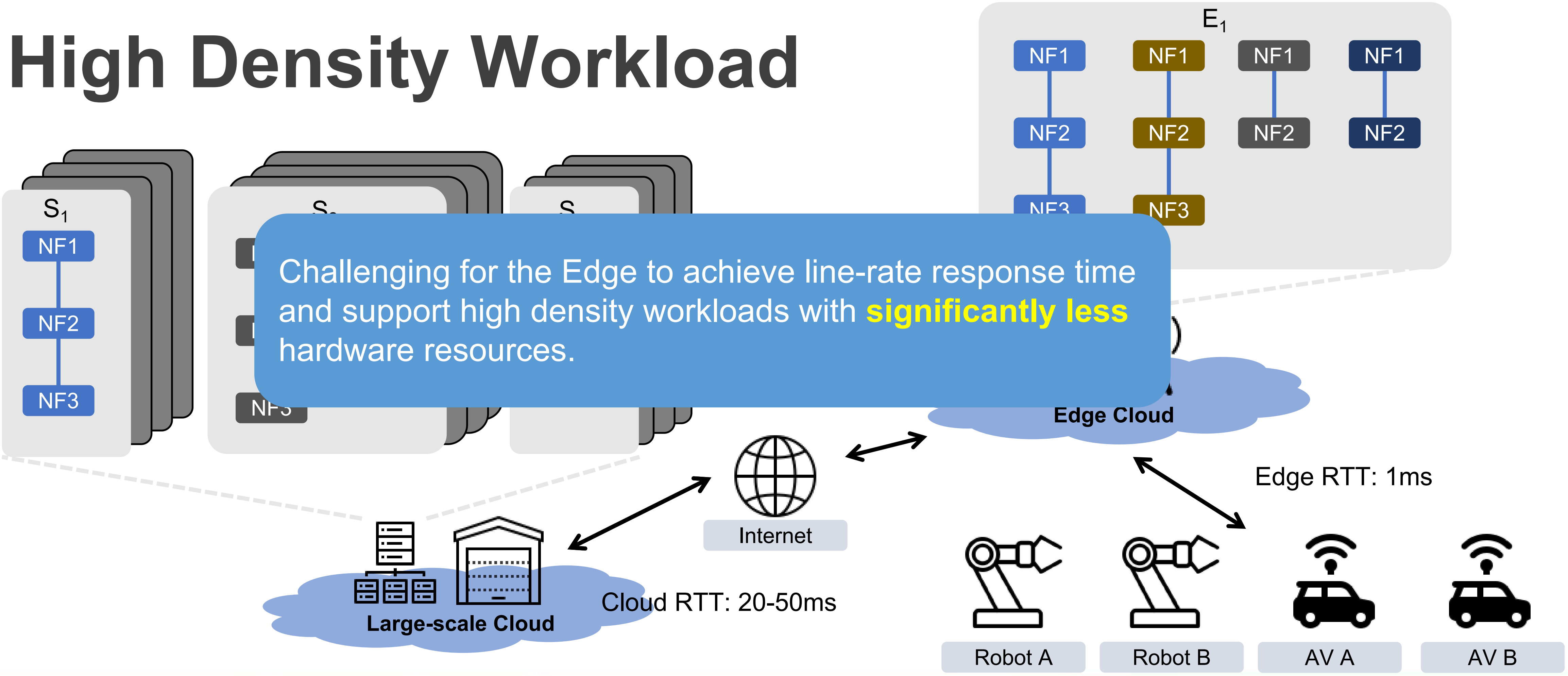


High Density Workload

Challenging for the Edge to achieve line-rate response time and support high density workloads with **significantly less** hardware resources.



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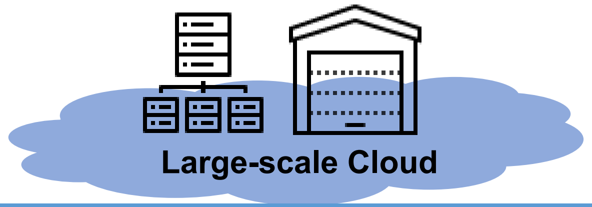

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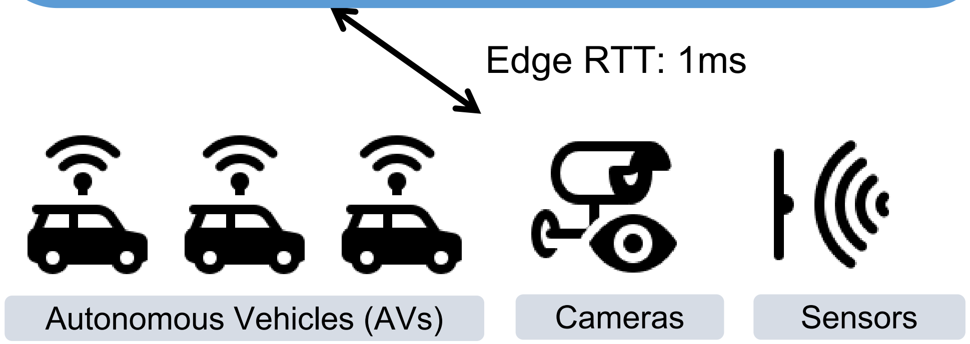
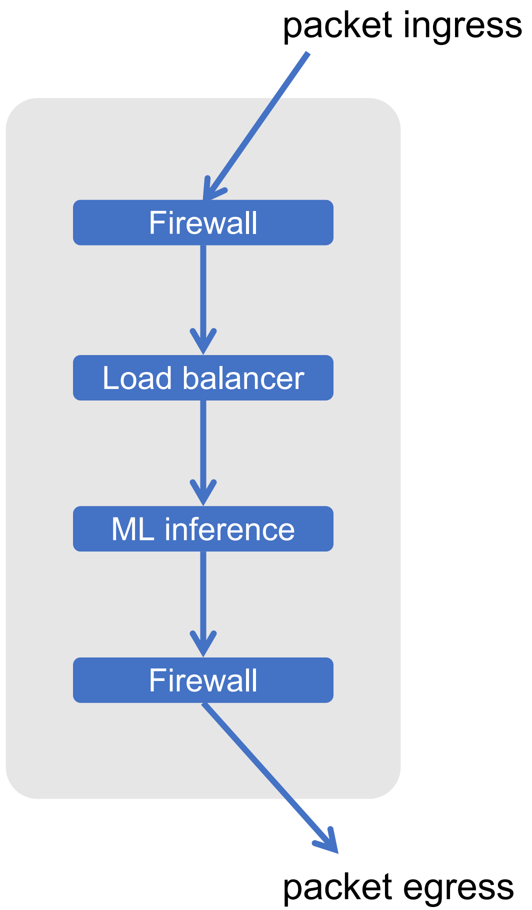


Deadline-aware Scheduling

Why challenging?

1. Chains of computations span cores.

2. Must meet end-to-end deadline of packets.



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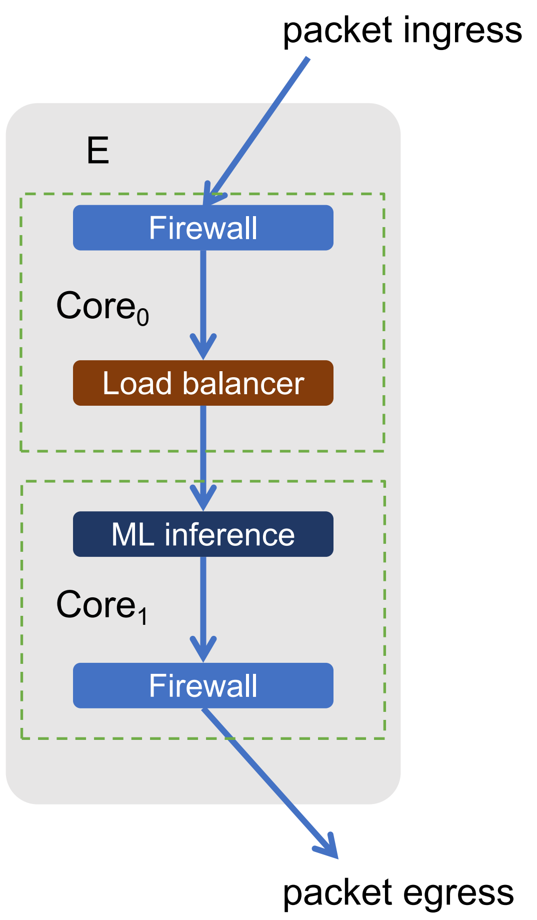

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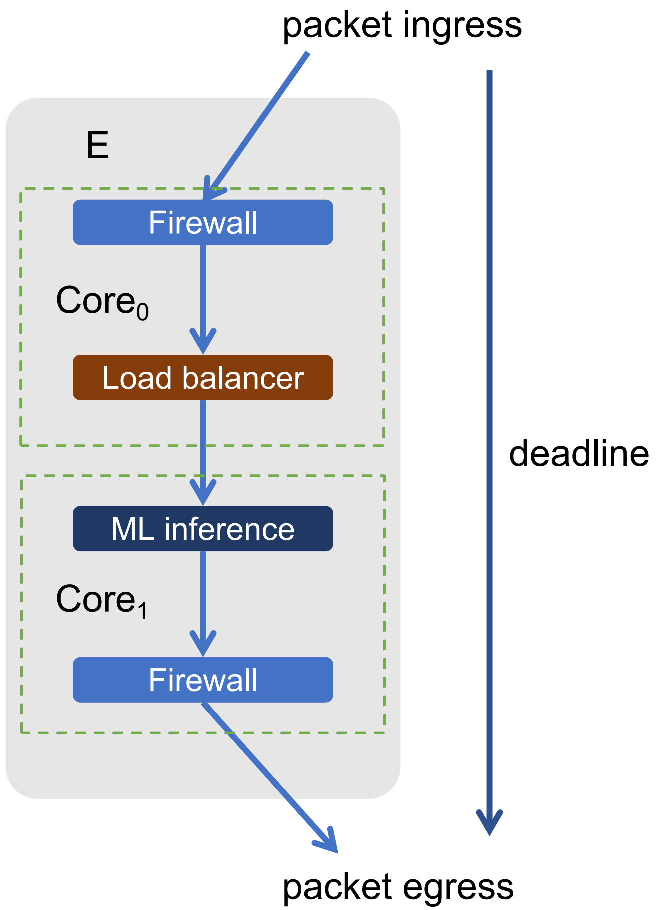

Existing Technologies

1. Optimize throughput by reducing system overhead.
    - Kernel bypass networking.
    - In-kernel Sandbox.
2. Thread-based deadline-aware scheduling.

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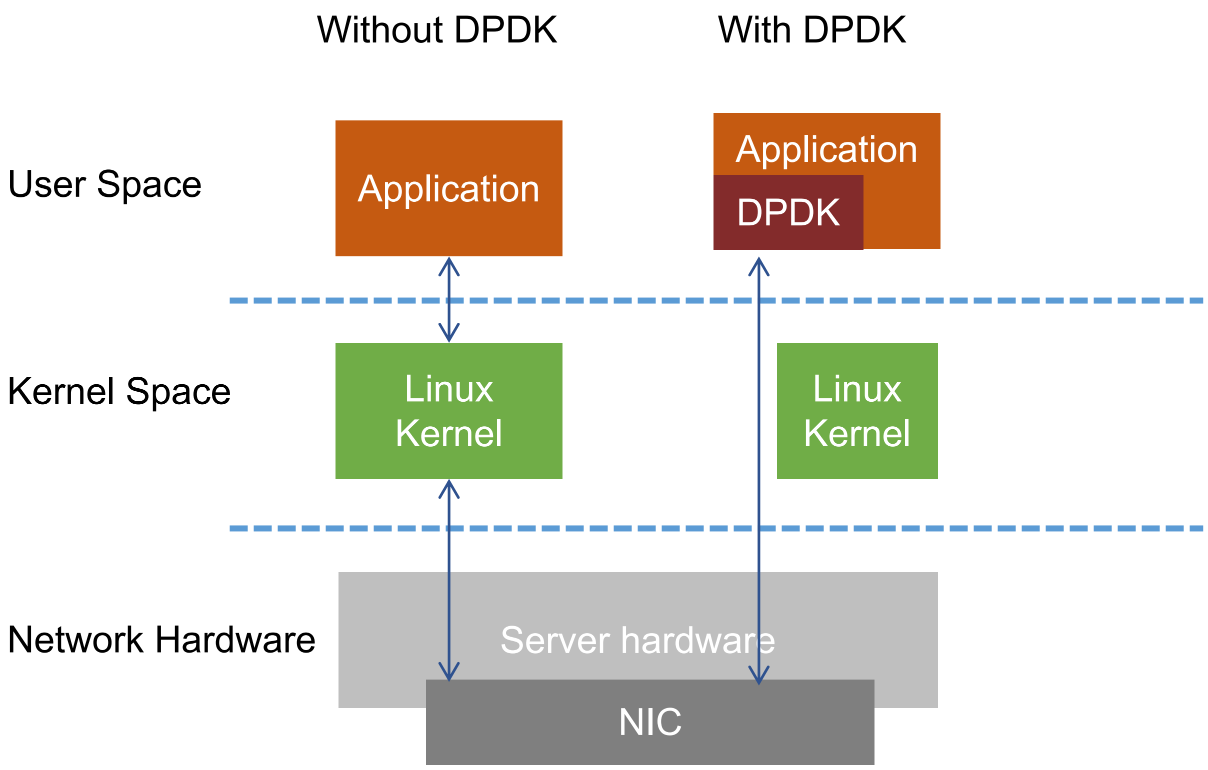
Data Plane Development Kit (DPDK)



Kernel bypass Networking

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- Achieving isolation between tenants.
  1. **DPDK + Single Root I/O Virtualization (SR-IOV)**

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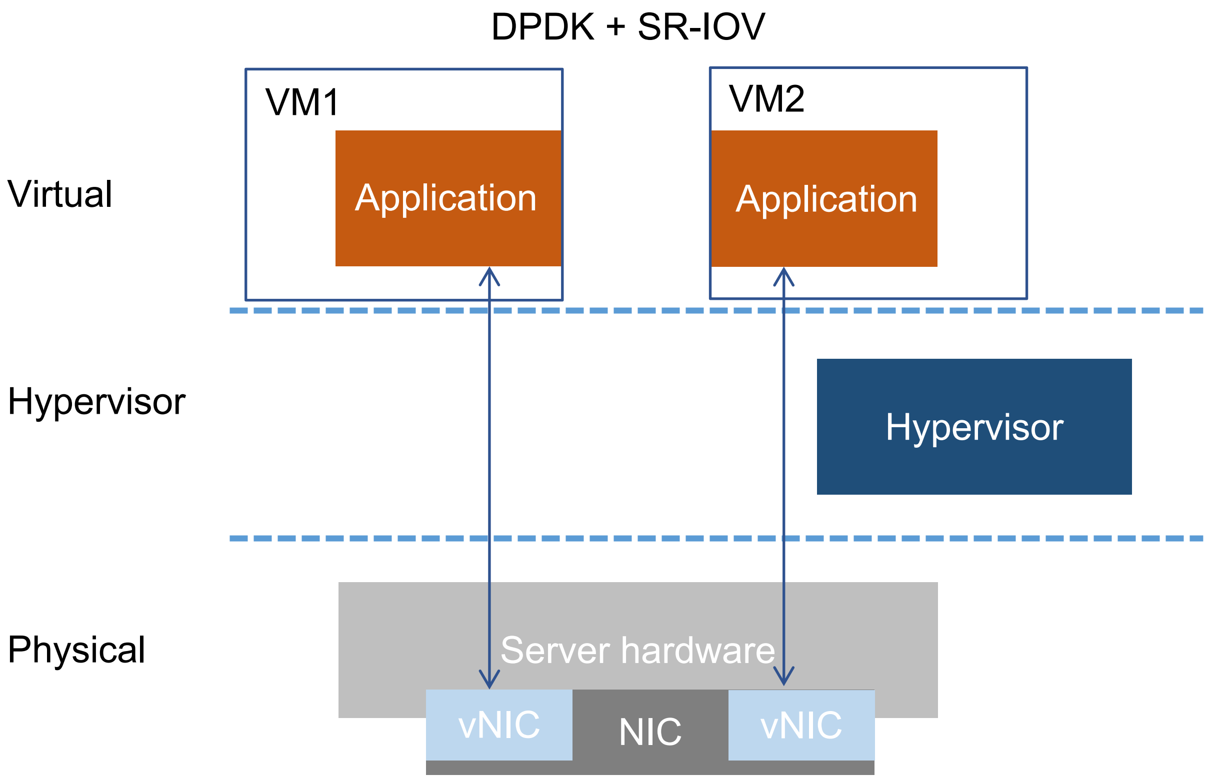

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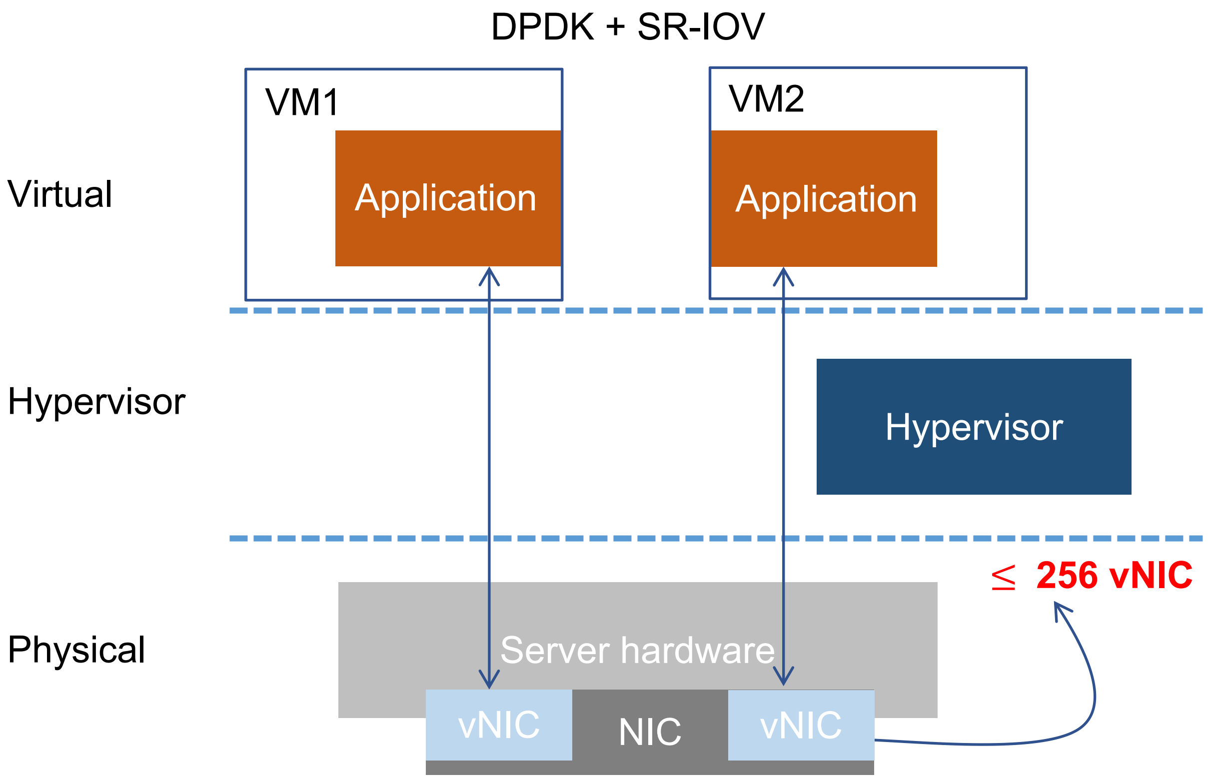
Data Plane Development Kit (DPDK)

- Achieving isolation between tenants.
  1. **DPDK + Single Root I/O Virtualization (SR-IOV)**
     - Multi-tenancy: ✔
     - Scalability: ✘
     - Deadline-aware: ✘
  2. DPDK + Open vSwitch (OVS)



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Data Plane Development Kit (DPDK)

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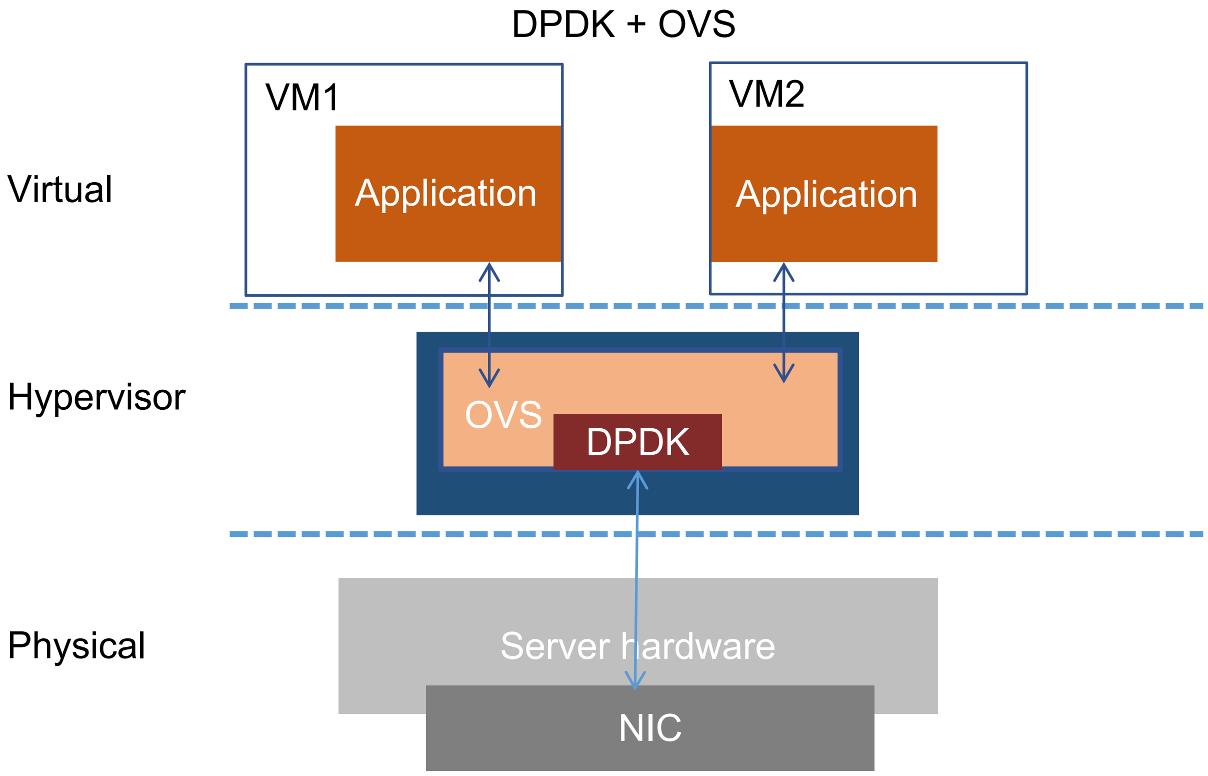

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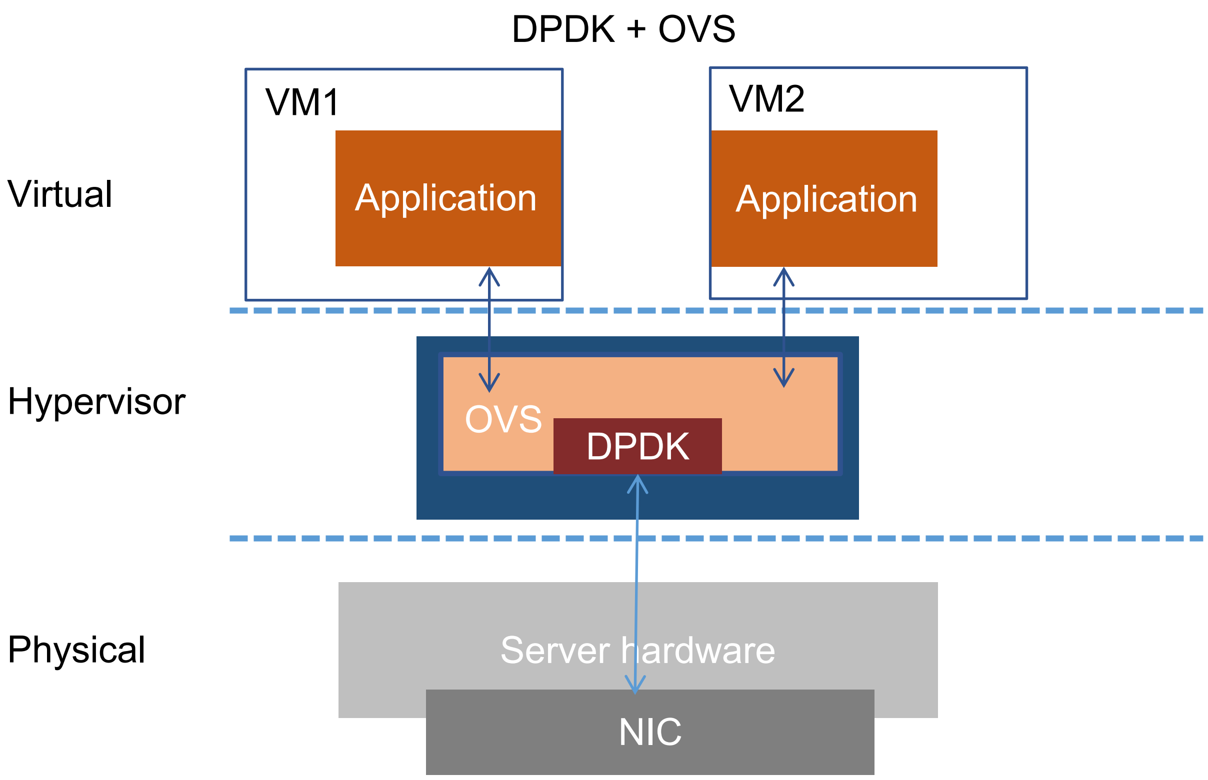
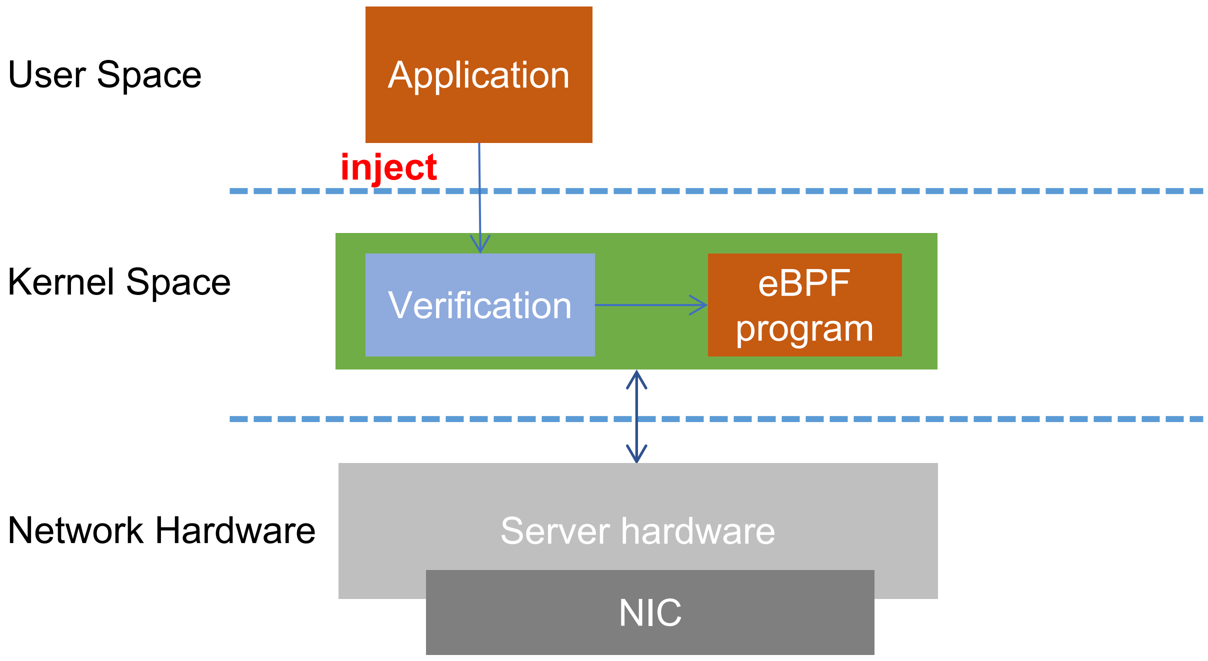


In-kernel Sandbox

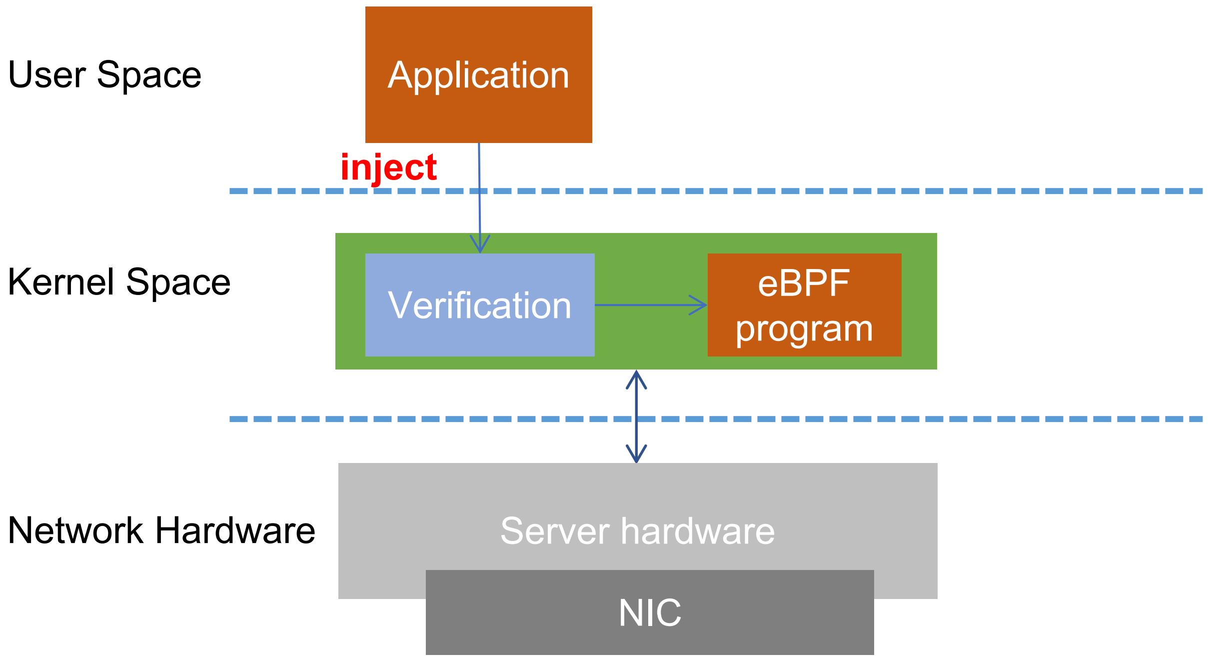
extended Berkeley Packet Filter (eBPF)



In-kernel Sandbox

extended Berkeley Packet Filter (eBPF)

- Evaluation:
  - Multi-tenancy: ❌
  - Deadline-aware: ❌



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   - Kernel bypass networking. ❌
   - In-kernel Sandbox. ❌

2. Thread-based deadline-aware scheduling.

Thread-based Scheduling.

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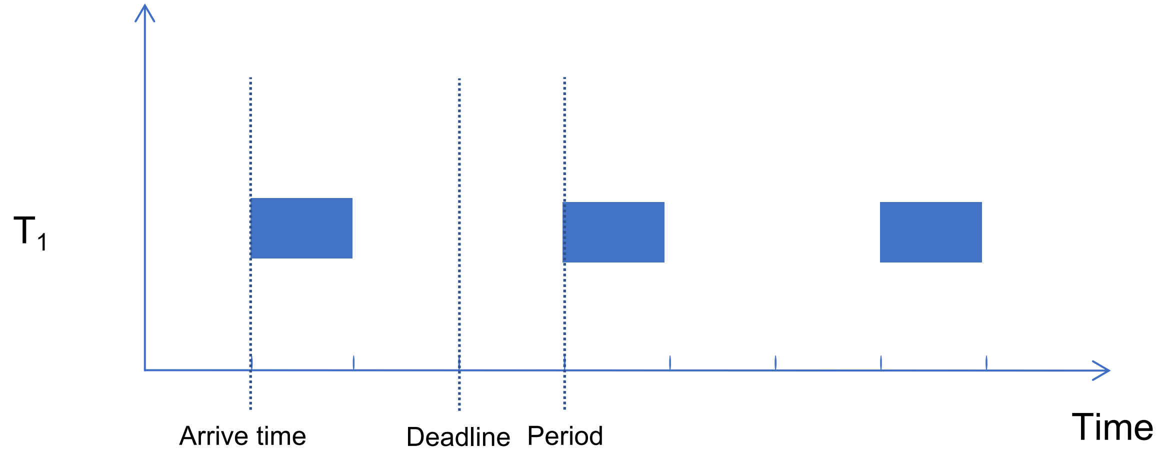
Multi-tenancy: ✓

Scalability: ✗

Dynamic workload: ✗

Periodic tasks with known execution time



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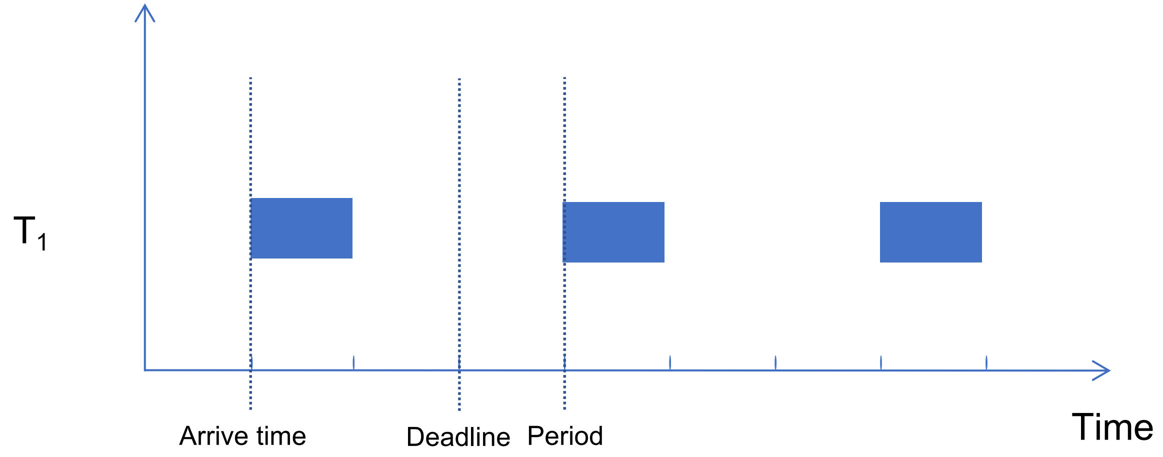

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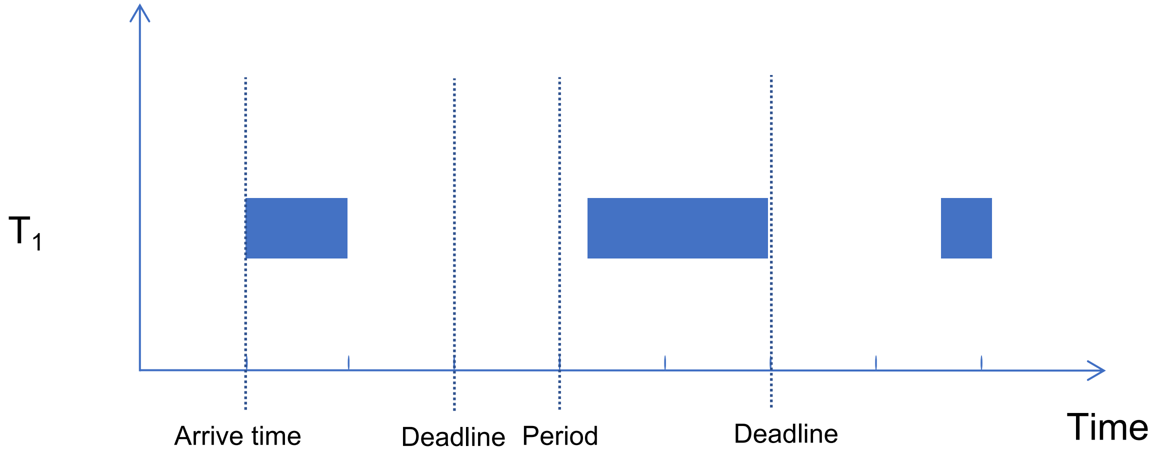

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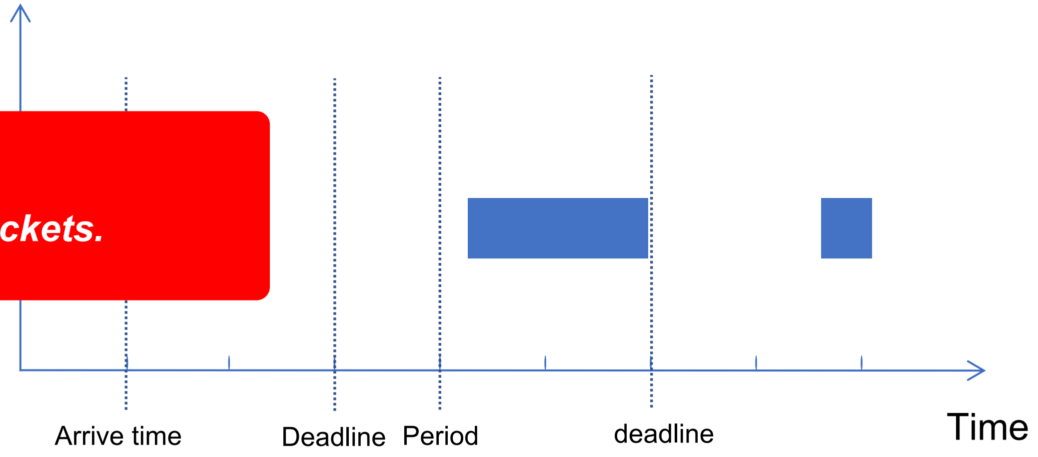

Core Problem:
Schedule ***tasks*** instead of ***packets.***

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1. Background:
   - Built upon EdgeOS:
     1. Light-weighted isolation abstraction: feather weight process (FWP),
     2. DPDK-based fast networking,
     3. Fast memory movement between FWPs.
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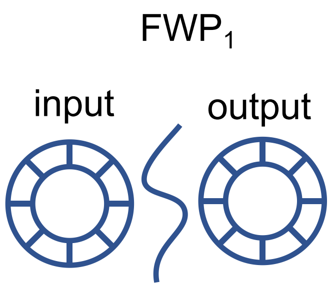

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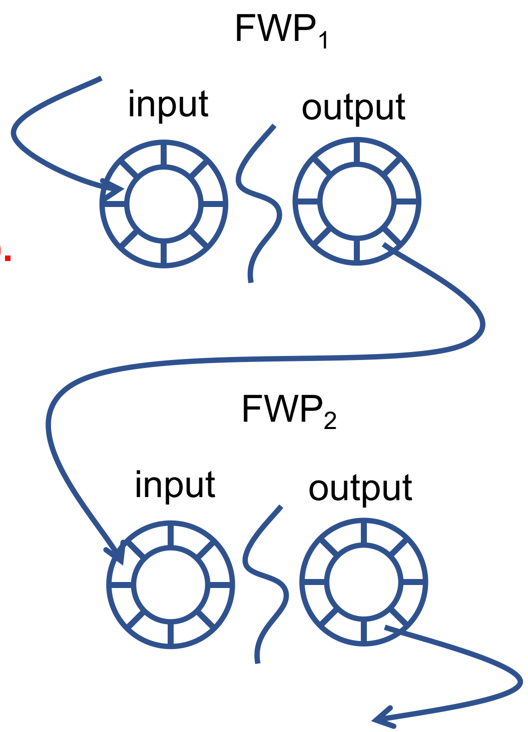

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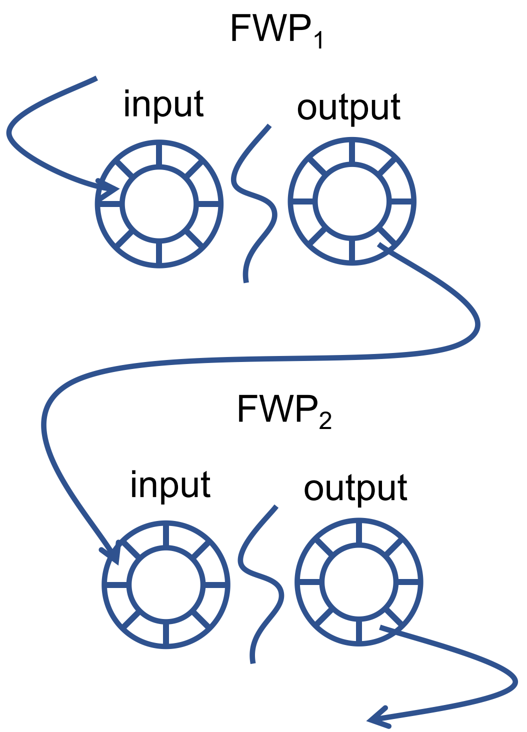

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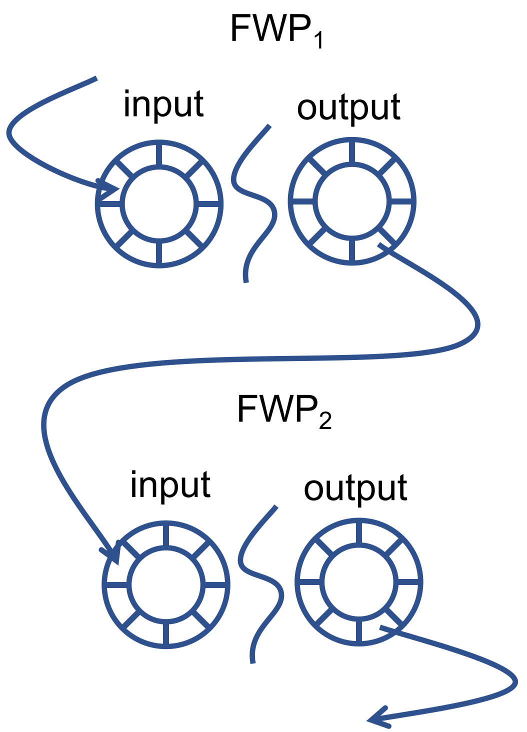

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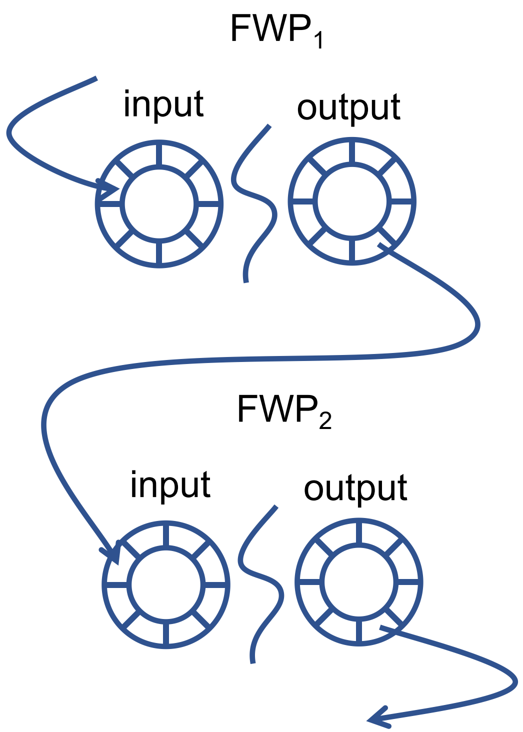
2. Goal: End-to-end deadline scheduling of packets.



End-to-end Packet Scheduling

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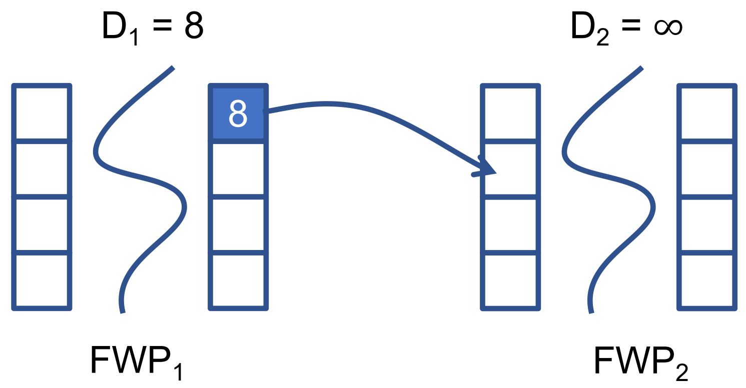
- Thread inherit deadline from the packet.

2. Schedule chains of computations.



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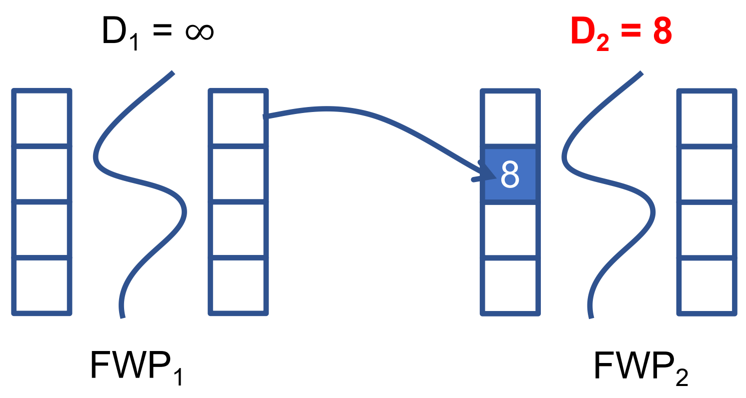

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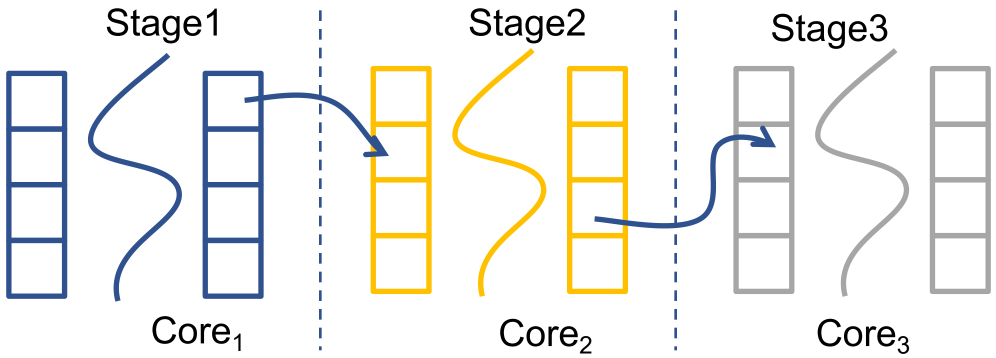

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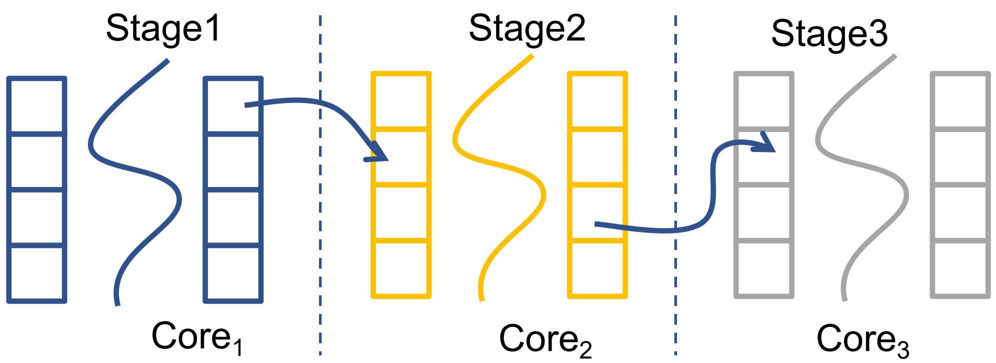

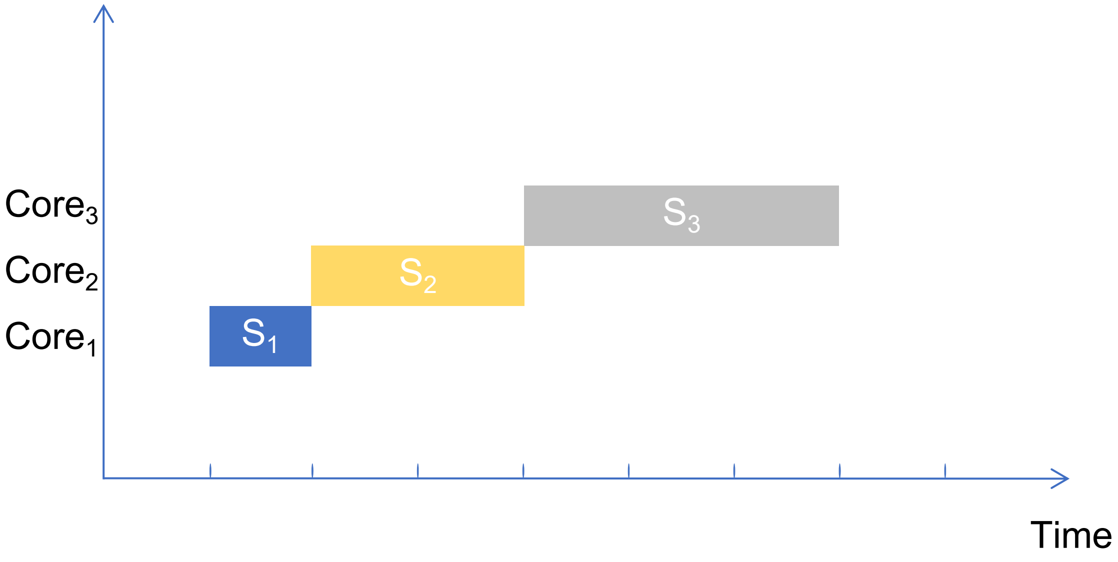

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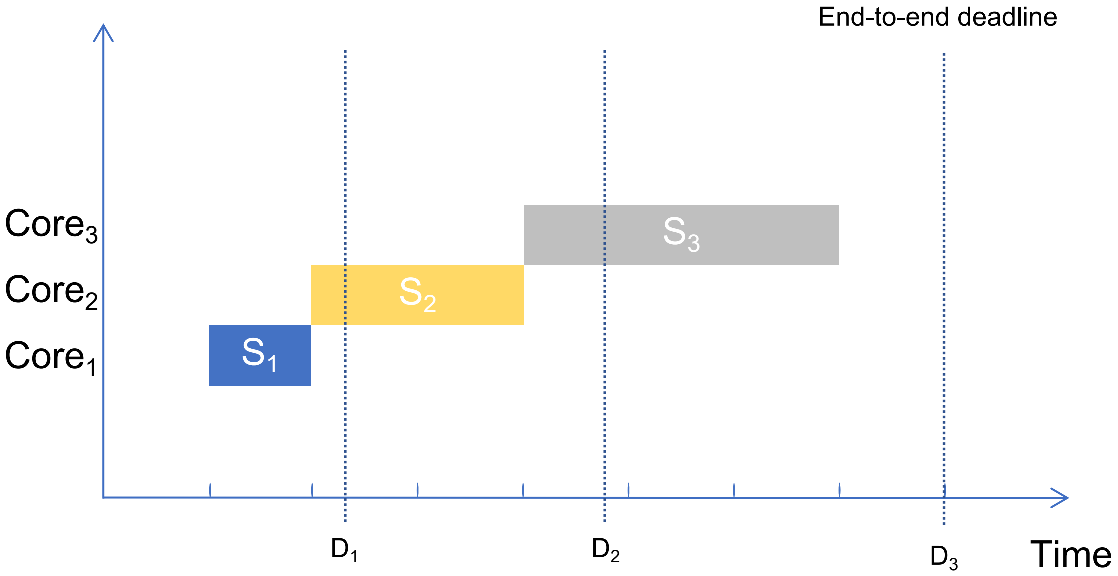

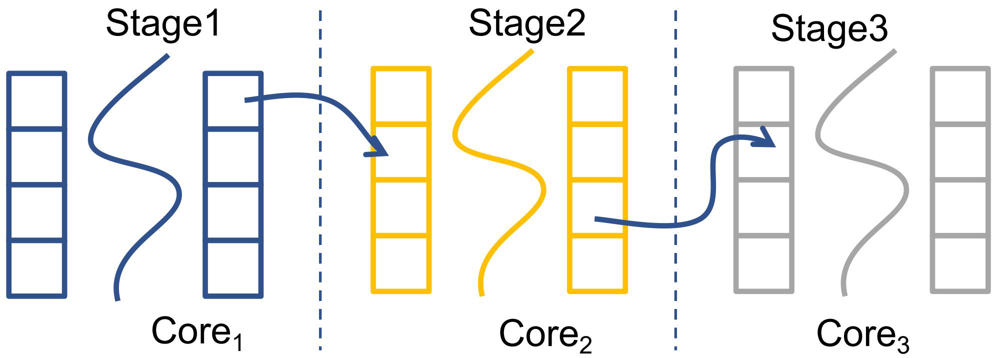

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2. Schedule chains of computations.
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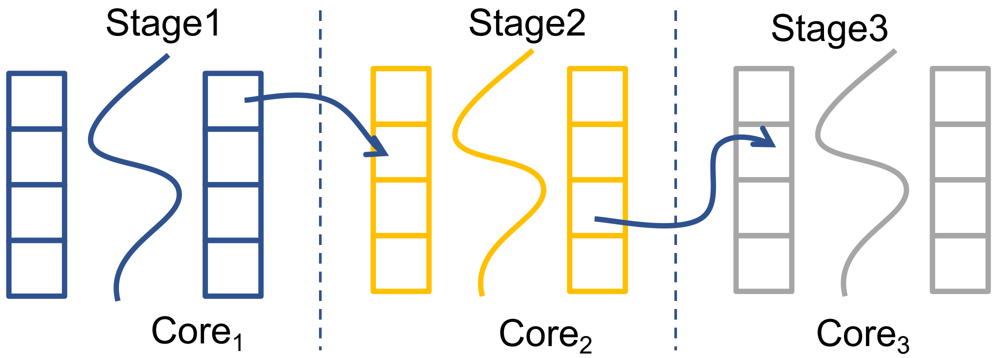
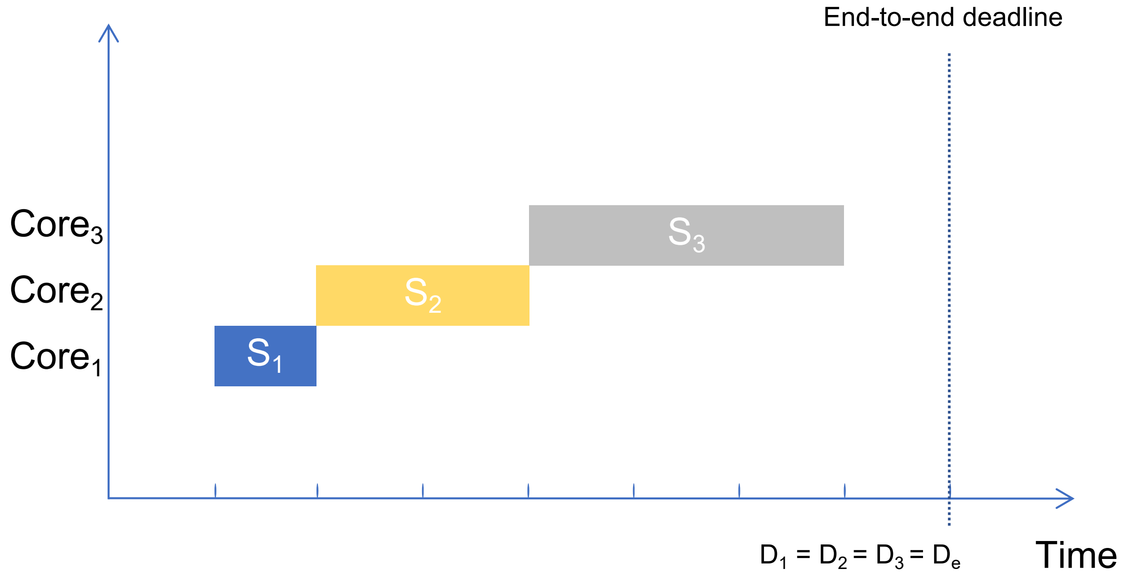
- Makes no assumption based on WCET.

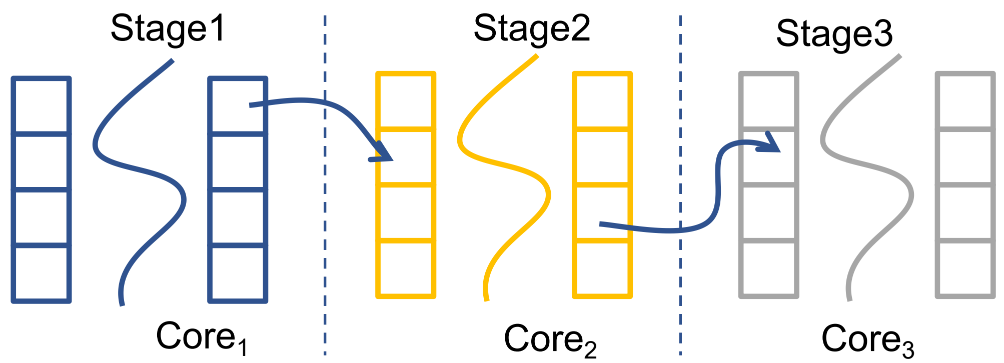


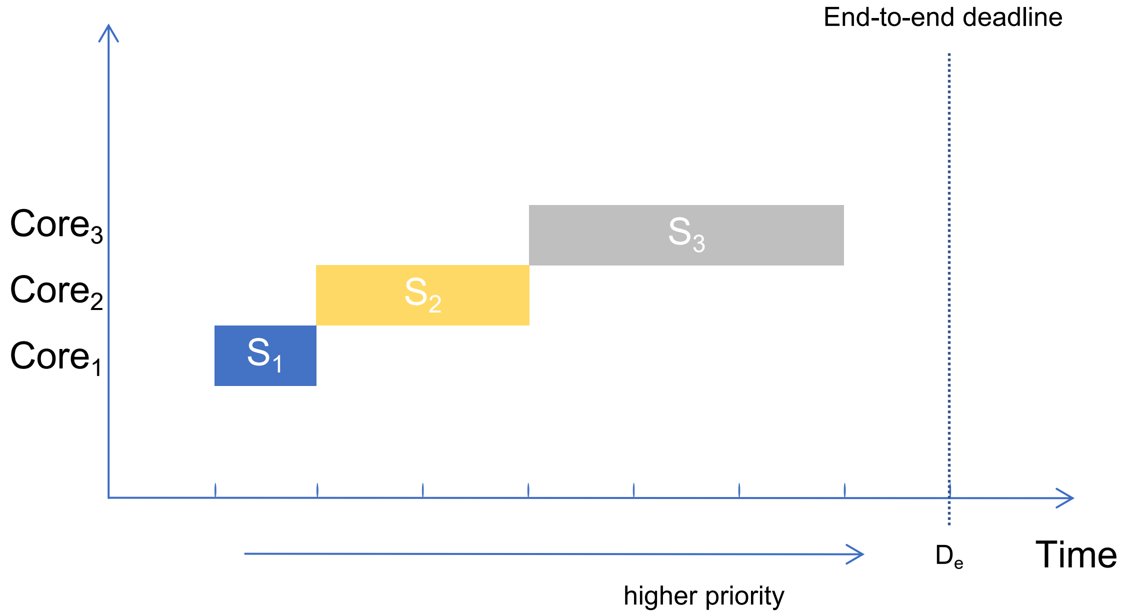


End-to-end Packet Scheduling

1. Deadline inheritance.
    - Thread inherit deadline from the packet.

2. Schedule chains of computations.
    - Same deadline for all stages.
    - Makes no assumption based on WCET.





Remaining Challenges

1. Frequent thread activation and deactivation.

2. Frequent (inter-core) event notification.

3. EDF policy overheads for frequent activation.

Optimization

1. Frequent thread activation and deactivation.

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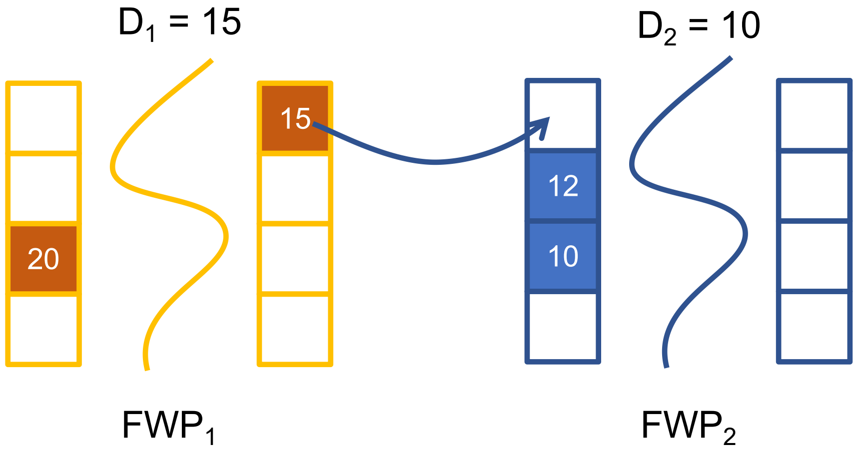
1. **Deadline-aware batching.**

2. Periodic Event Notification.

3. Constant-Time EDF.

Deadline-aware batching

1. **Deadline inheritance of multiple packets.**
2. Priority inversions (Δ_{batch}).
3. Batching with controlled size.



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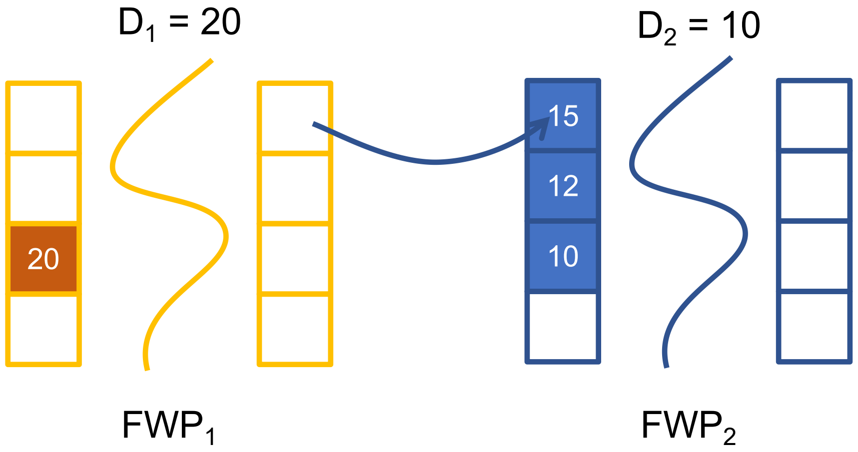

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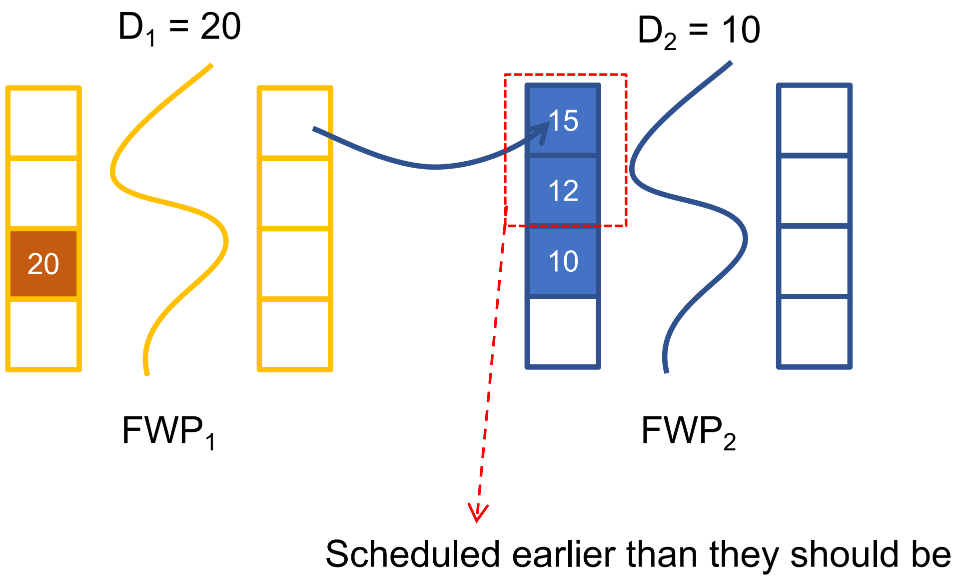

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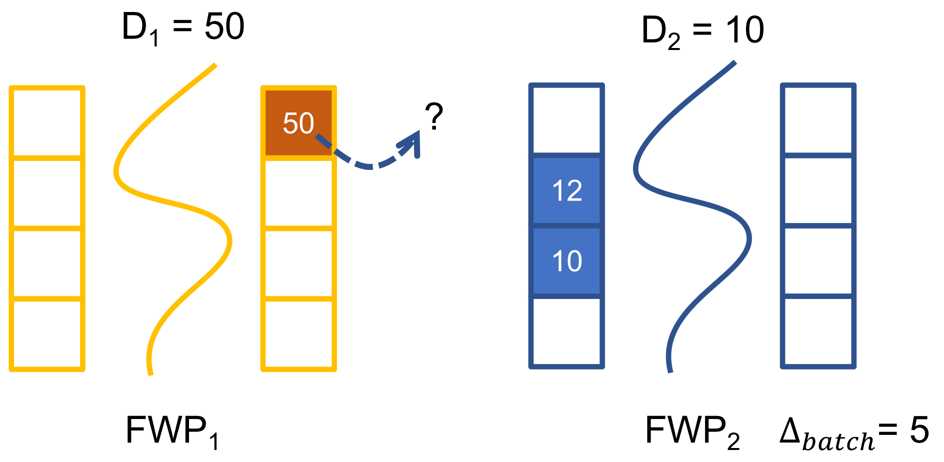

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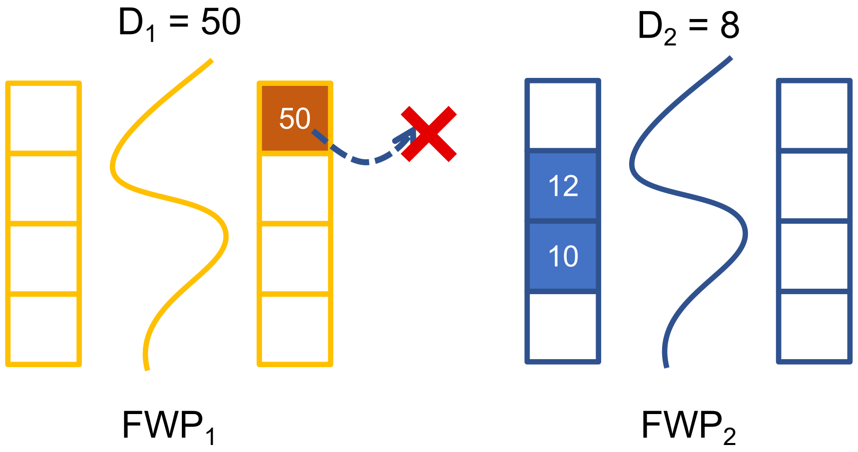

$(P_i, d_i), d \in [d_i - \Delta_{batch}, d_i]$

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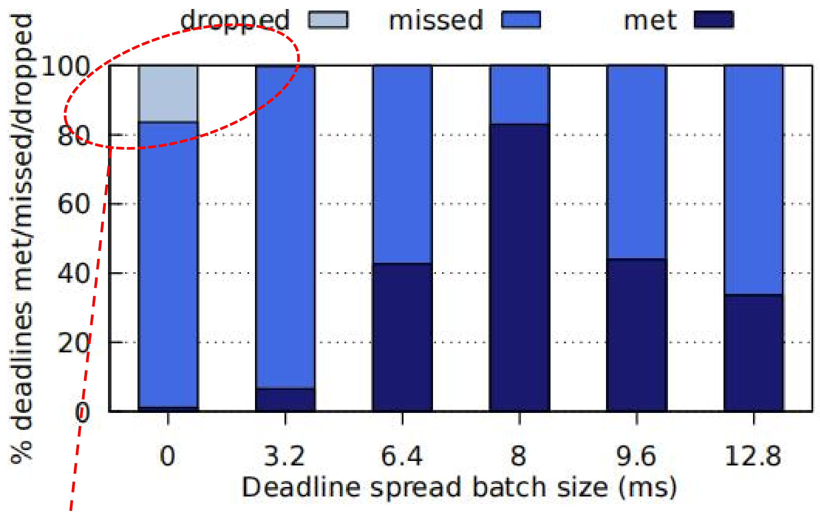

Caused by System overhead

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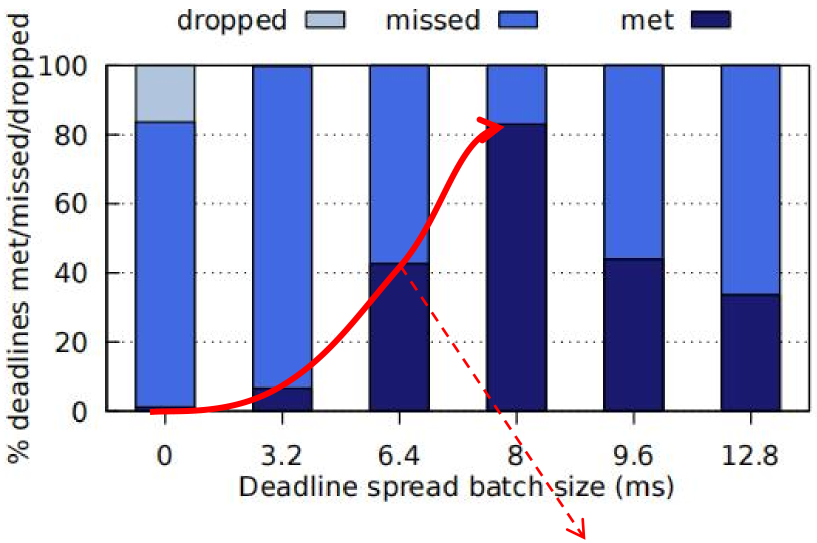

Batching reduces system overhead

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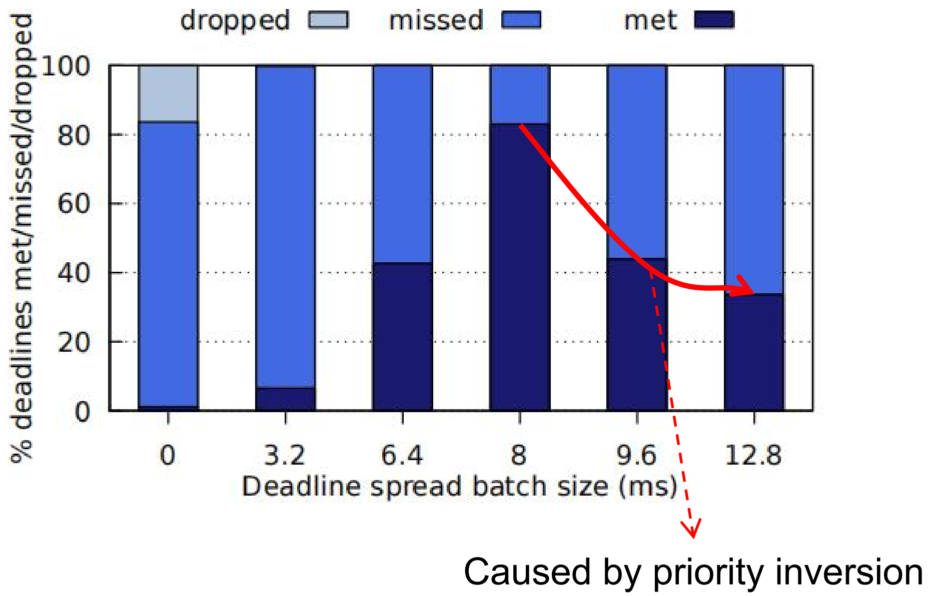

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3. Constant-Time EDF.

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Constant-time EDF Scheduling (CT-EDF)

1. **Quantize time into fixed quanta.**
2. Using array to track each quanta.
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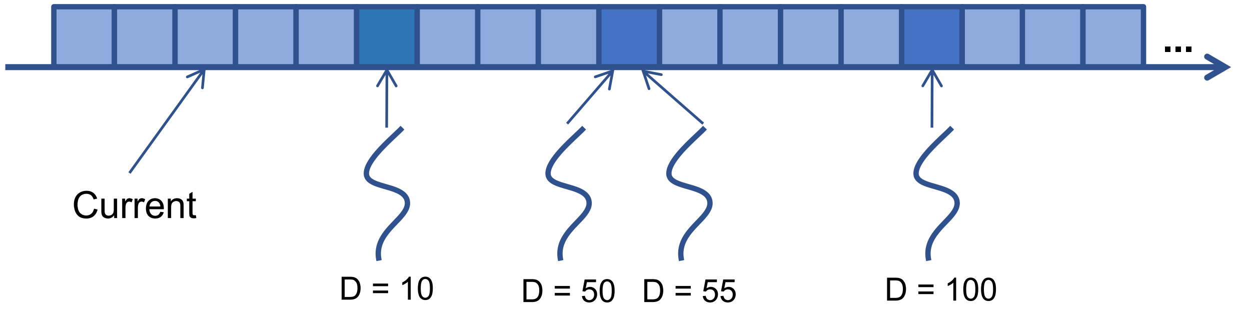

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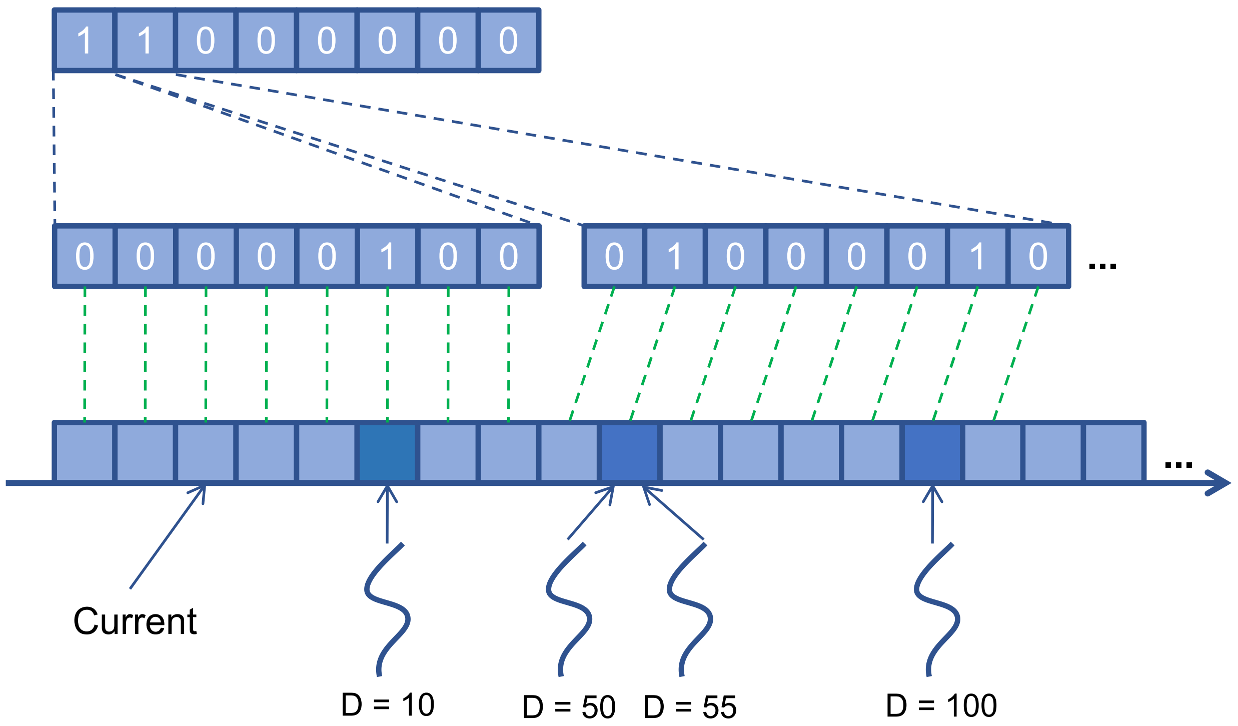

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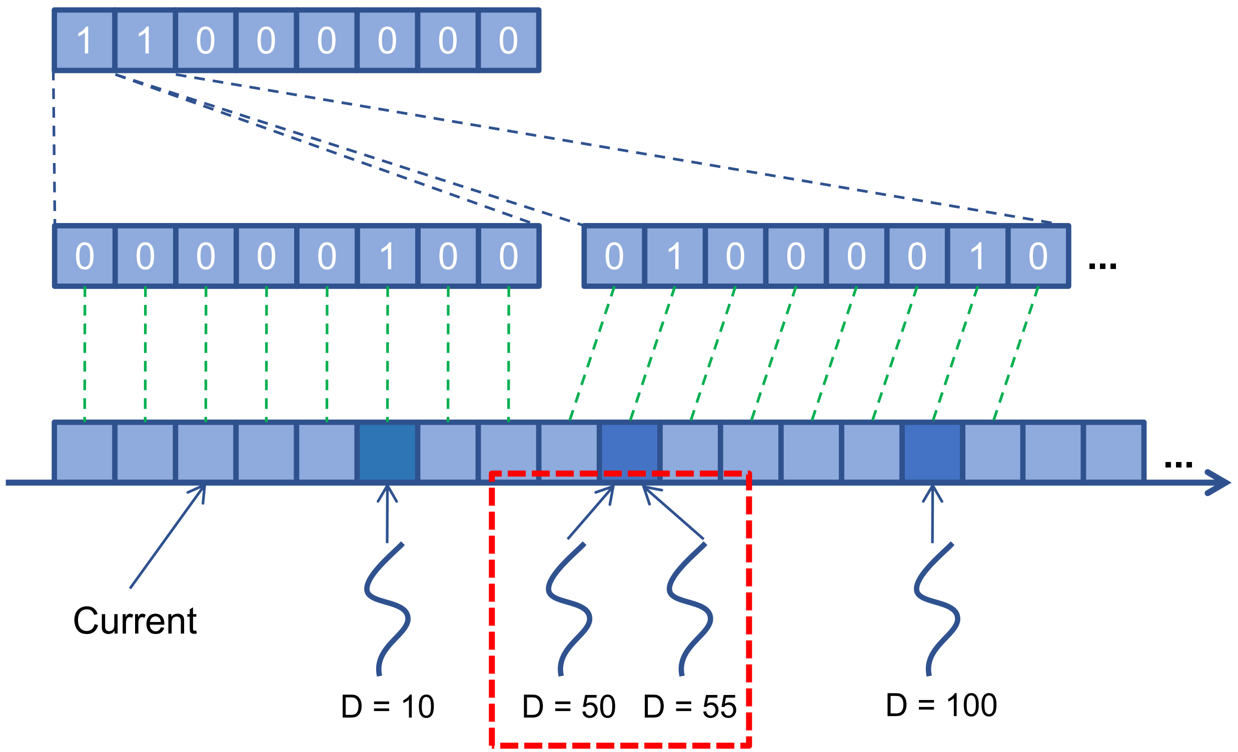

Priority Inversions

Edge-RT achieves line-rate throughput by creating ***bounded*** deadline inversions:

1. Batching (Δ_{batch}).
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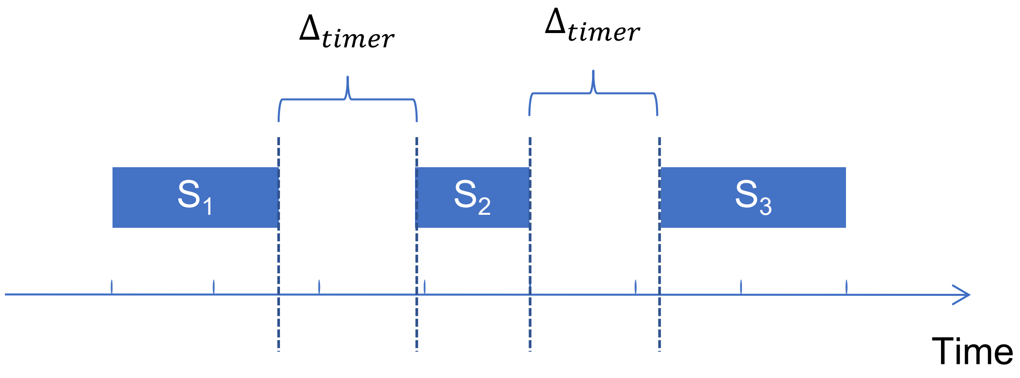
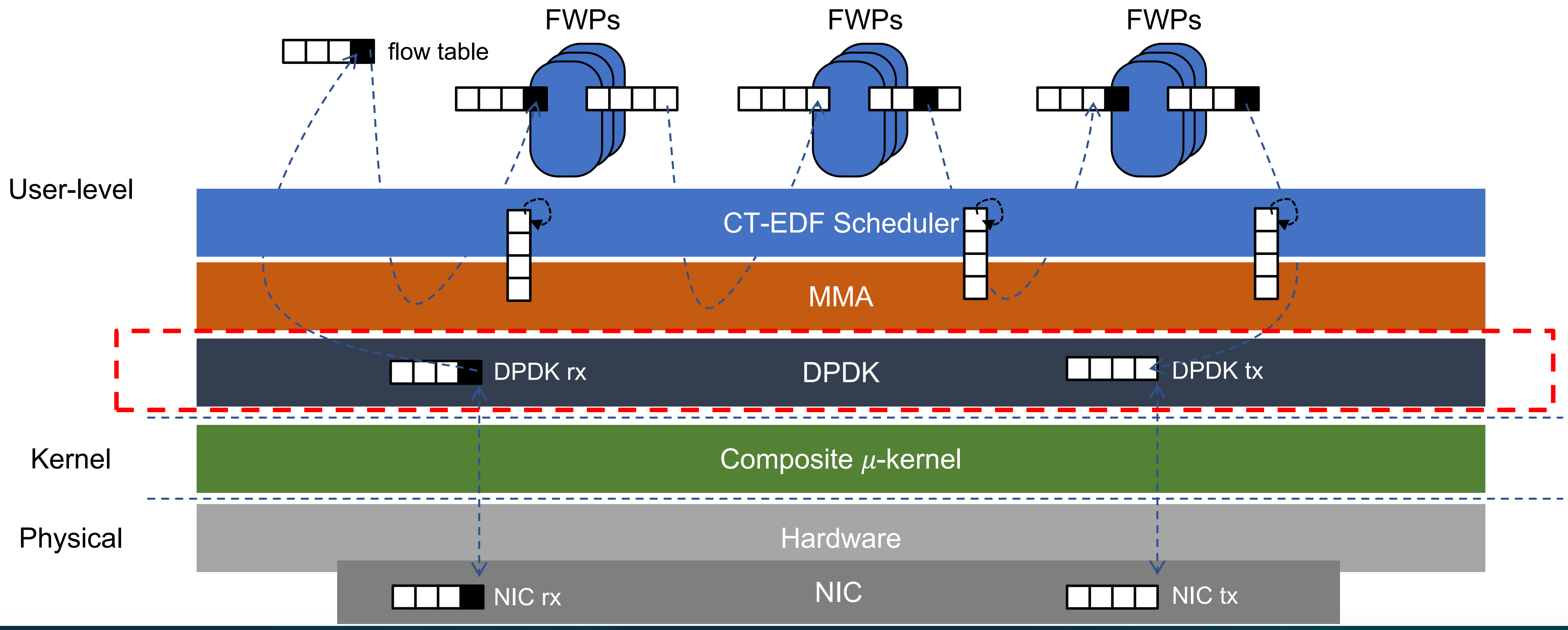


$$d \in [d_i - max(\Delta_{batch}, \Delta_{window}), d_i]$$

System Architecture



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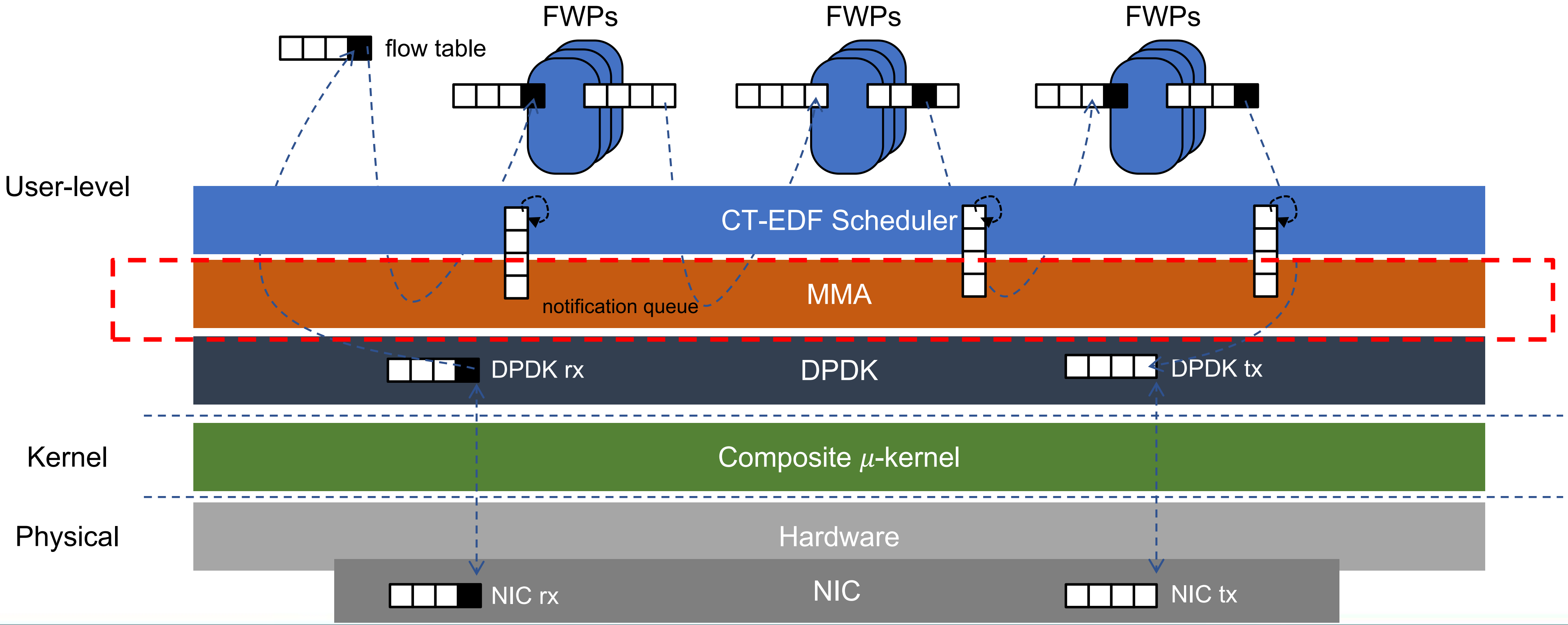

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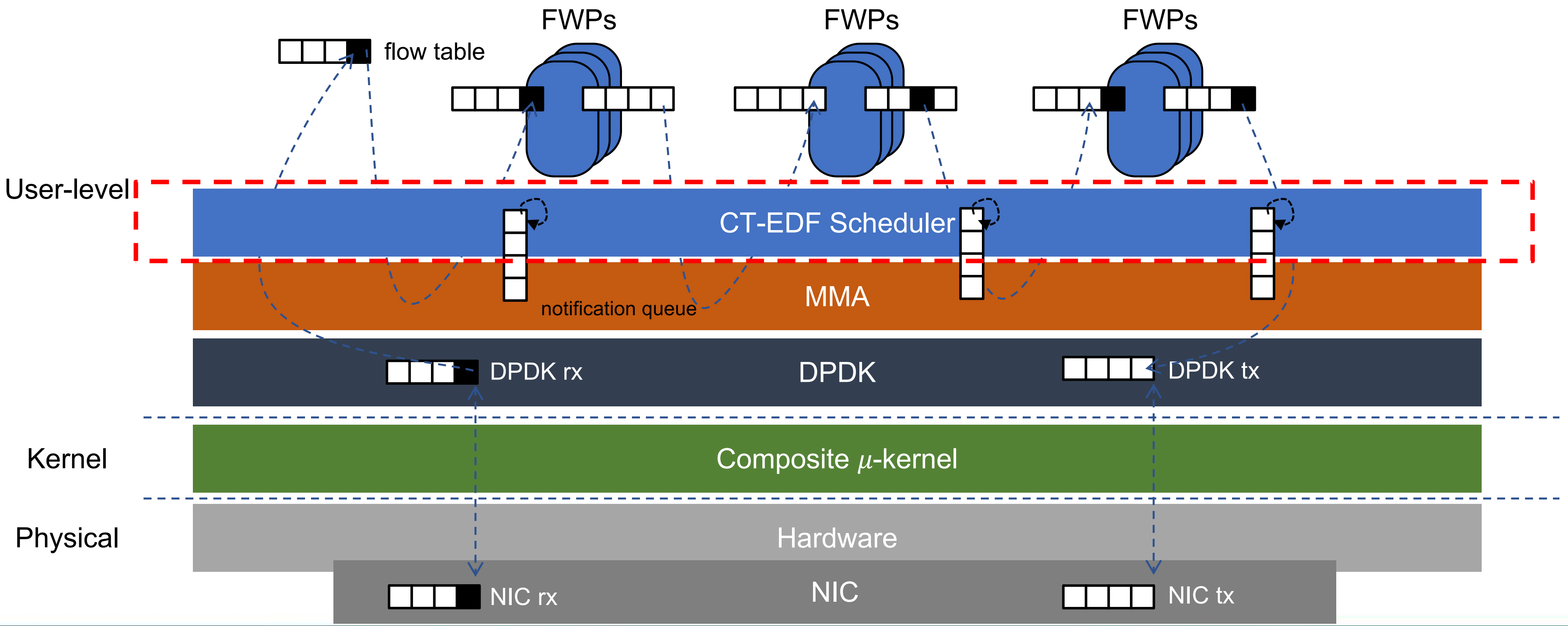

Evaluation

Experiment setup:

- Power Edge R740 servers.
- Two socket Intel(R) Xeon(R) Platinum 8160 CPUs @2.10GHz each with 24 cores.
- Intel X710 for10GbE NIC.
- Compare Linux, EdgeOS and Edge-RT

Evaluation

Workload description:

1. Bimodal workloads.
2. Light computation $WCET = 40\mu s, deadline = 10ms$, (Kalman filtering)
3. Heavy computation $WCET = 5ms, deadline = 500ms$, (ML inference)
4. EdgeRT $\Delta_{batch} = 8ms, \Delta_{timer} = 250\mu s$.
5. 480 clients/chains, chain length 4, 1920 FWPs in total.

Utilization Sensitivity

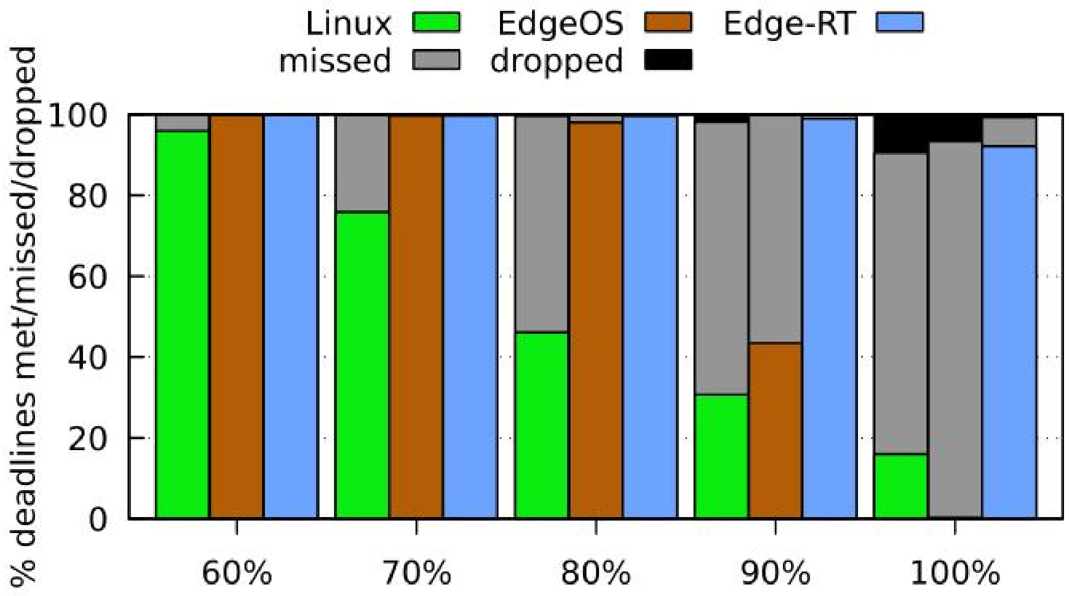

Fig.1. The behavior of **light** tasks with increasing utilization

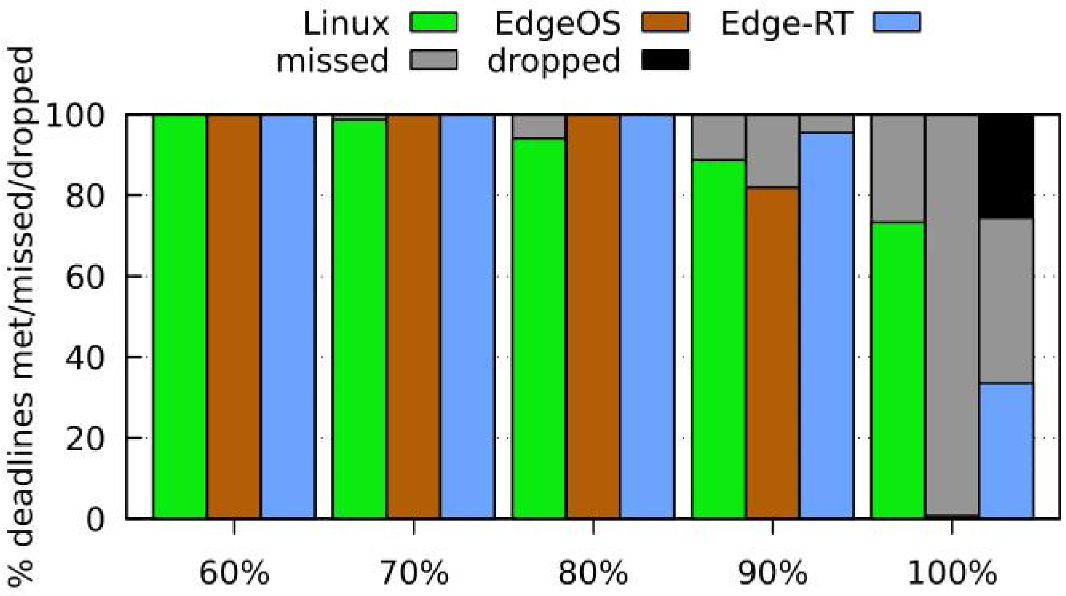

Fig.2. The behavior of **heavy** tasks with increasing utilization

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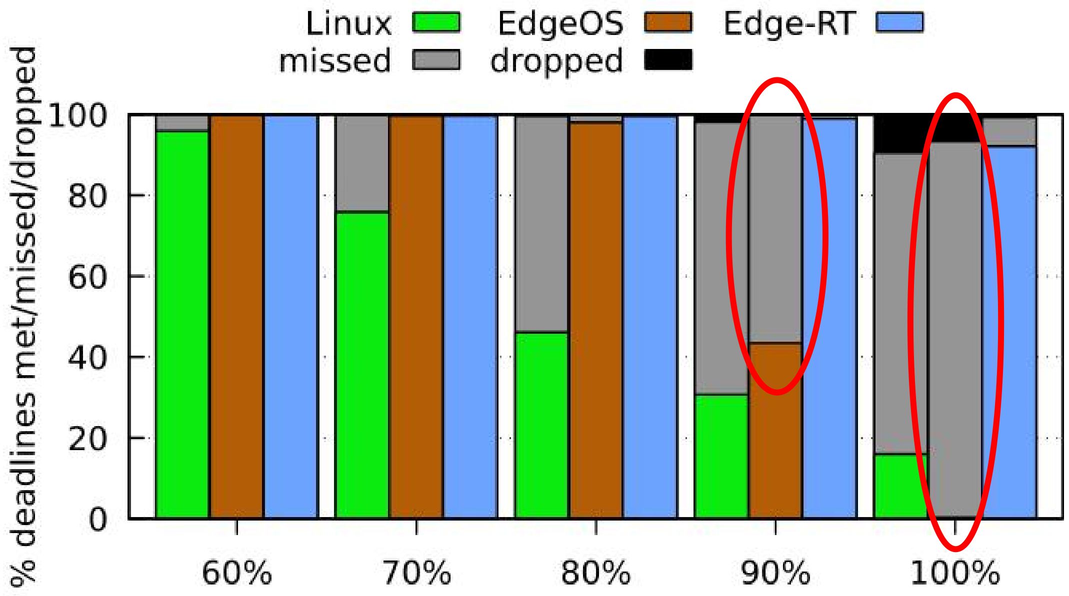

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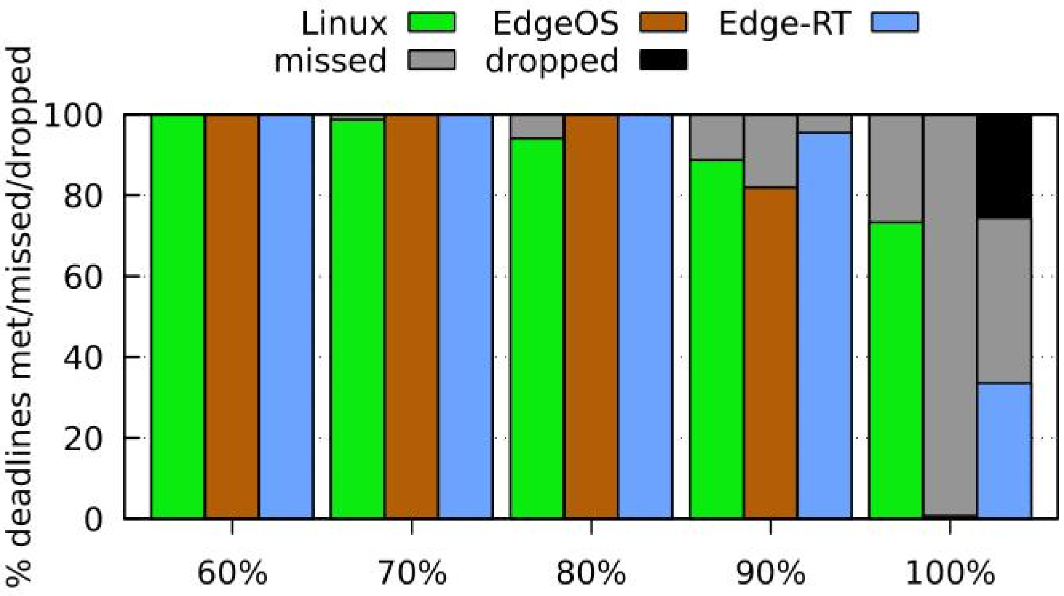

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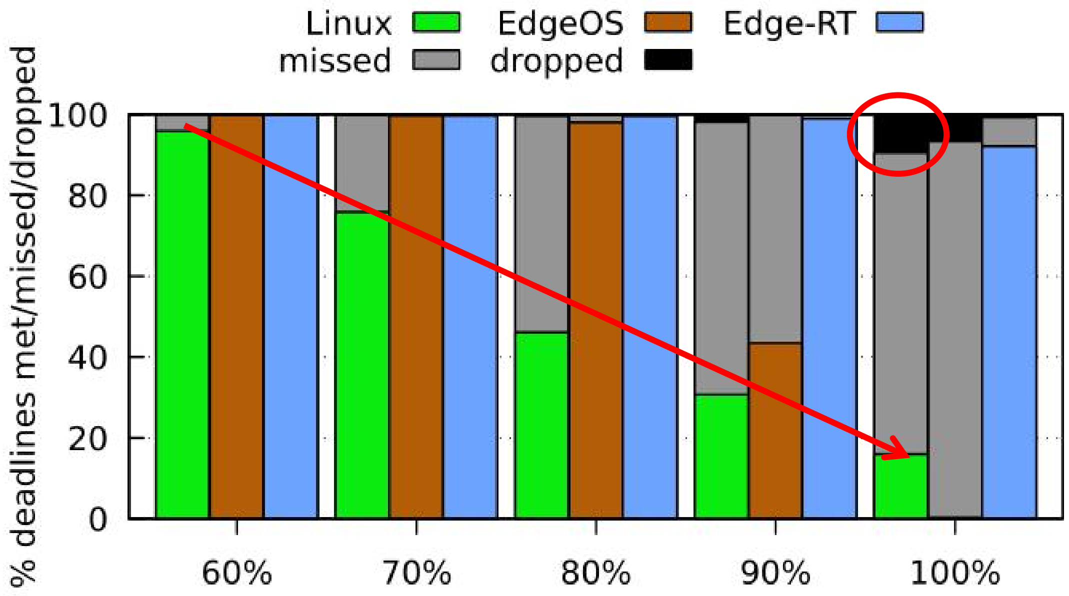

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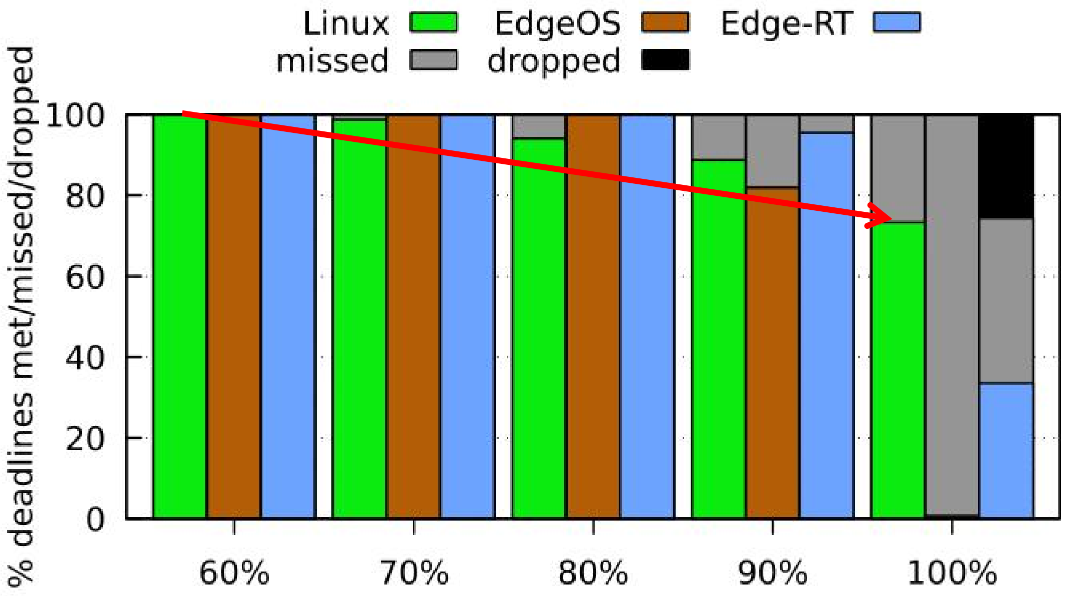

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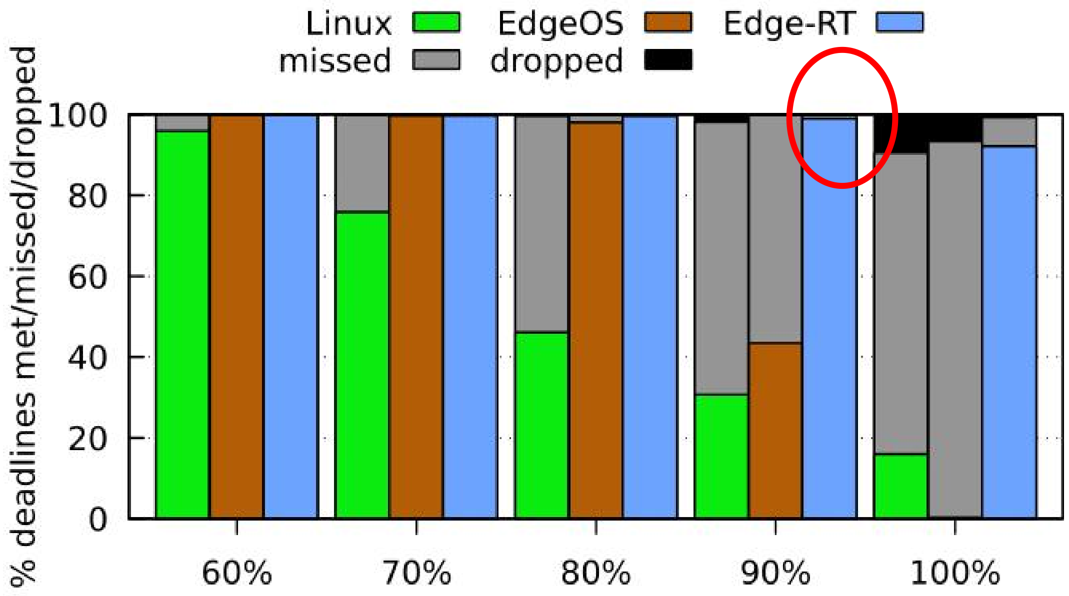

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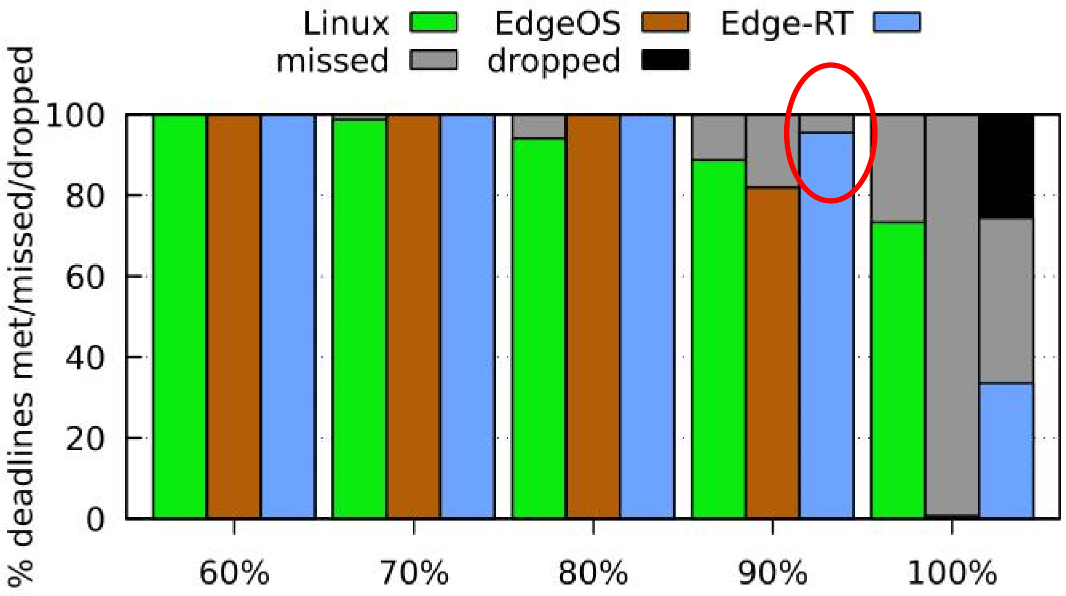

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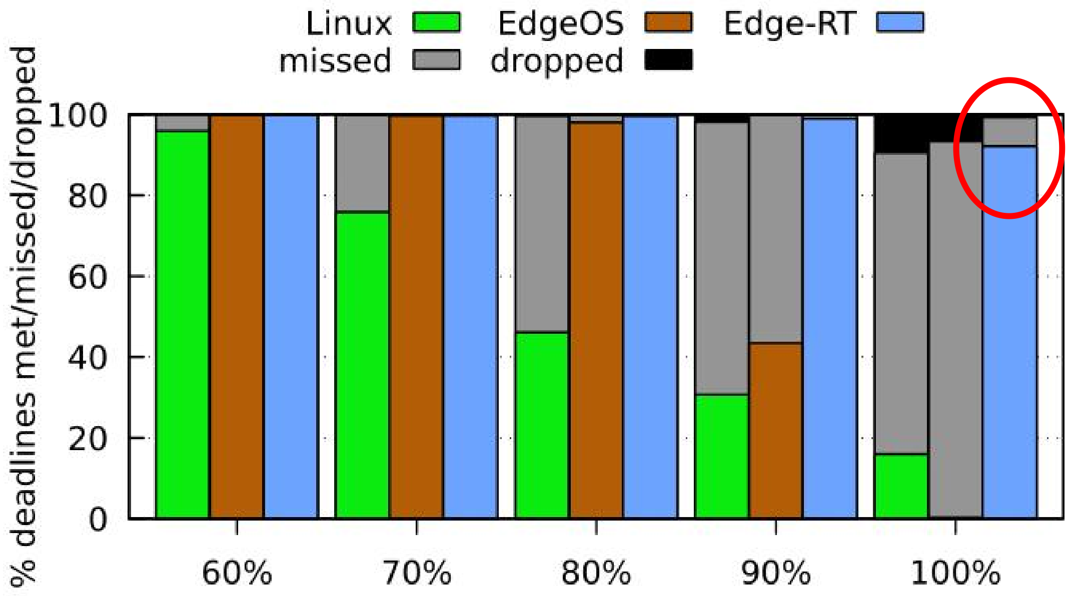

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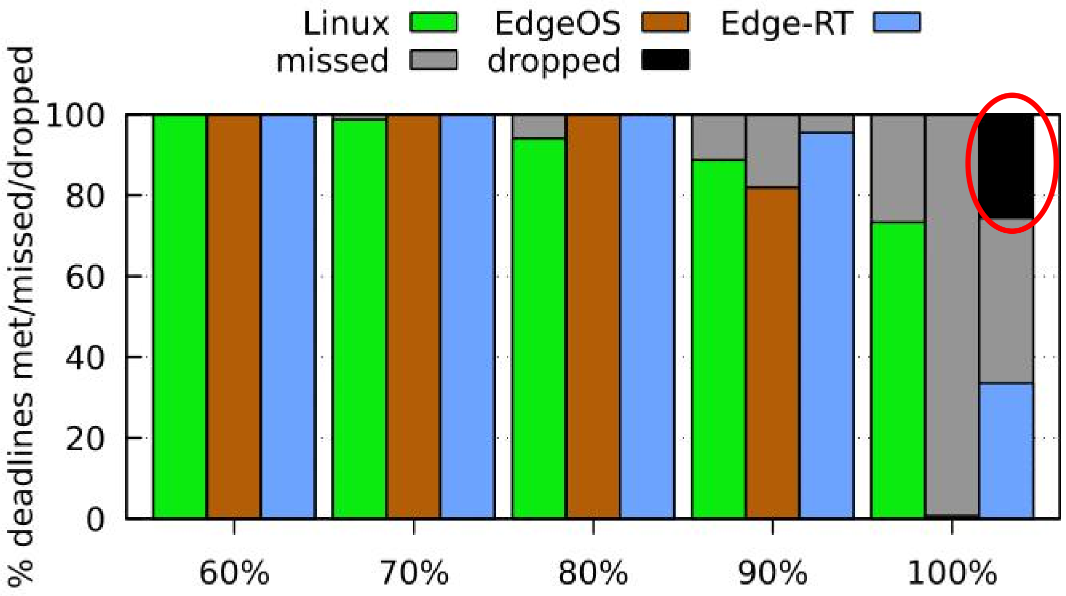

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Conclusion

Edge-RT provides a solution for the **multi-tenant**, **dense**, **latency-sensitive** edge cloud.

- Multi-tenant: Strong FWP-based isolation.
- Density: throughput-centric implementation.
- Deadlines:
    - FWP inheritance of packet deadlines,
    - Bounded deadline inversions,
    - End-to-end packet deadline scheduling.

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Edge-RT: strong foundation for the real-time edge

Questions and Comments?

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Existing Technologies

- A summary of edge-cloud configurations

Edge Configurations	Deadline-aware	Preemptivity	Client Isolation	Computation Chain	Dynamic Workloads	Scalability
CFS	not deadline-aware	preemptive	process-based	per-client chain	supported	> 2000
DPDK + OVS/SR-IOV	not deadline-aware	non-preemptive	process-based	no chain	supported	~ 256
SCHED_DEADLINE	per-thread	preemptive	process-based	no chain	not supported	< 1000
eBPF + XDP	not deadline-aware	non-preemptive	no isolation	no chain	not supported	-
EdgeOS	not deadline-aware	preemptive	FWP-based	per-client chain	supported	> 2000
Edge-RT	per-packet	preemptive	FWP-based	per-client chain	supported	> 2000