Smart (Programmable) NICs

ECE/CS598HPN

Radhika Mittal

FlexTOE: Flexible TCP Offload with Fine-Grained Parallelism

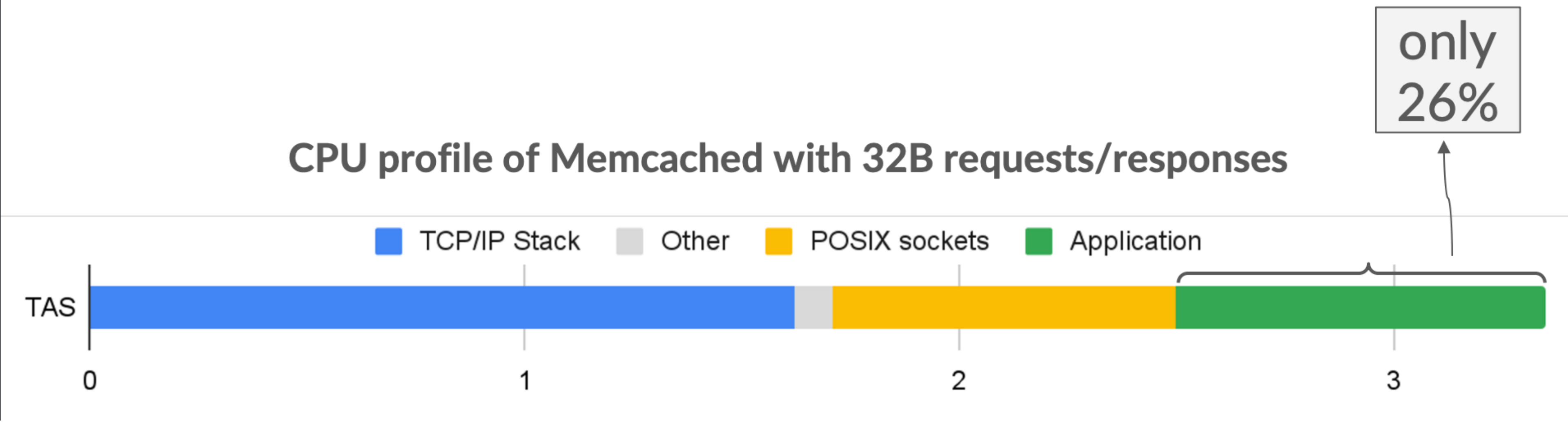
Rajath Shashidhara, Tim Stamler,
Antoine Kaufmann, Simon Peter

NSDI'22

Some of the content has been taken from Rajath's NSDI talk.

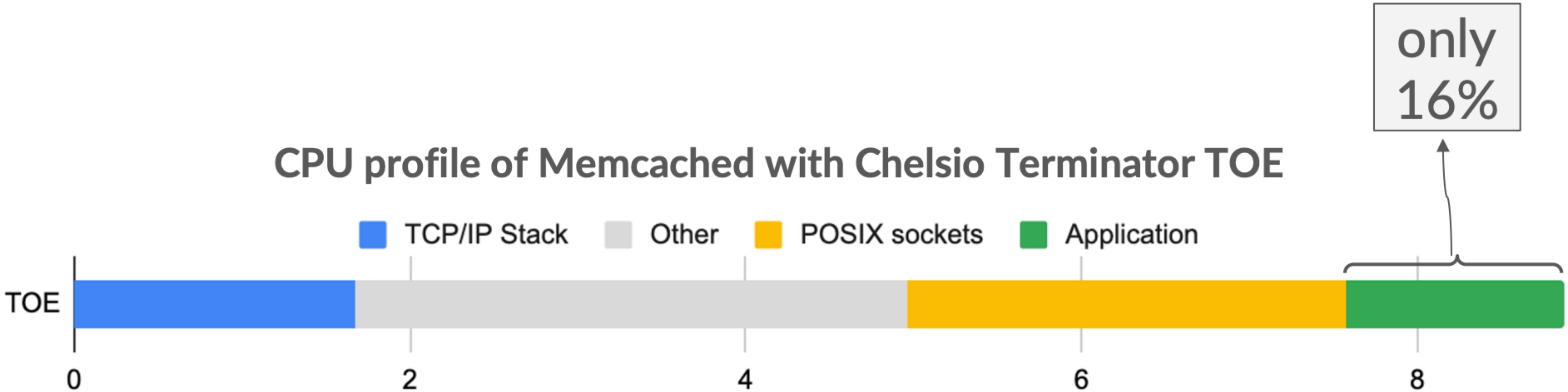
Motivation

- Software network stacks (including kernel bypass) have high CPU overhead.
  - Specifically evaluated Linux TCP and TAS



Motivation

- Existing TCP offload engines have limited flexibility (slow upgrade cycles).
  - Specifically evaluated Chelsio Terminator TOE



Motivation

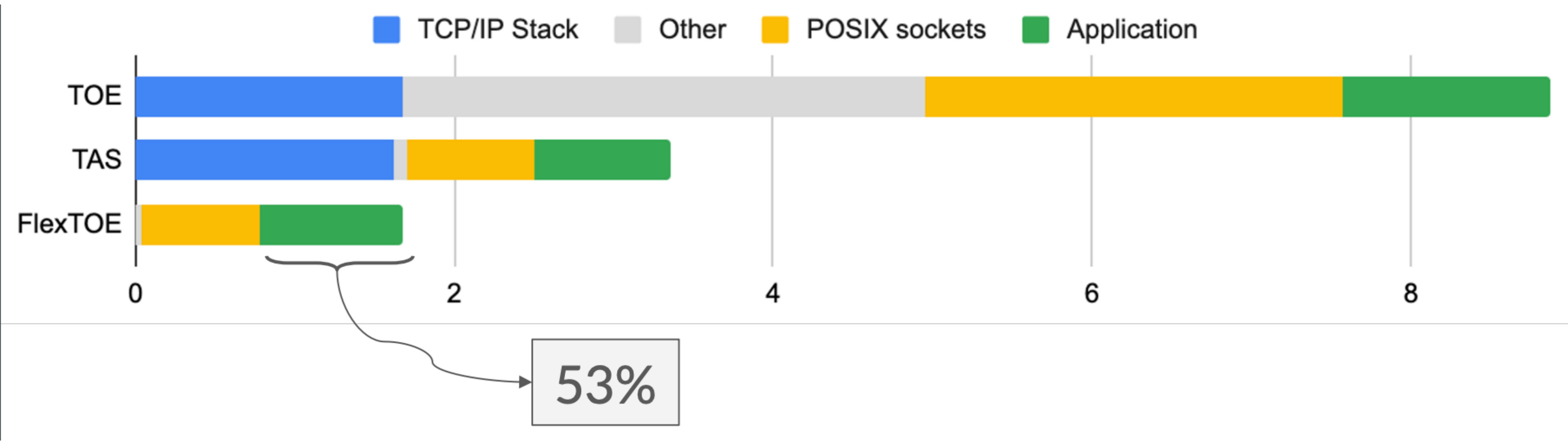
- Software network stacks (including kernel bypass) have high CPU overhead.

- Existing TCP offload engines have limited flexibility (slow upgrade cycles).

- *How to get both flexibility and performance?*

FlexTOE

- Flexible TCP offload on SoC-based smartNICs with network processors.

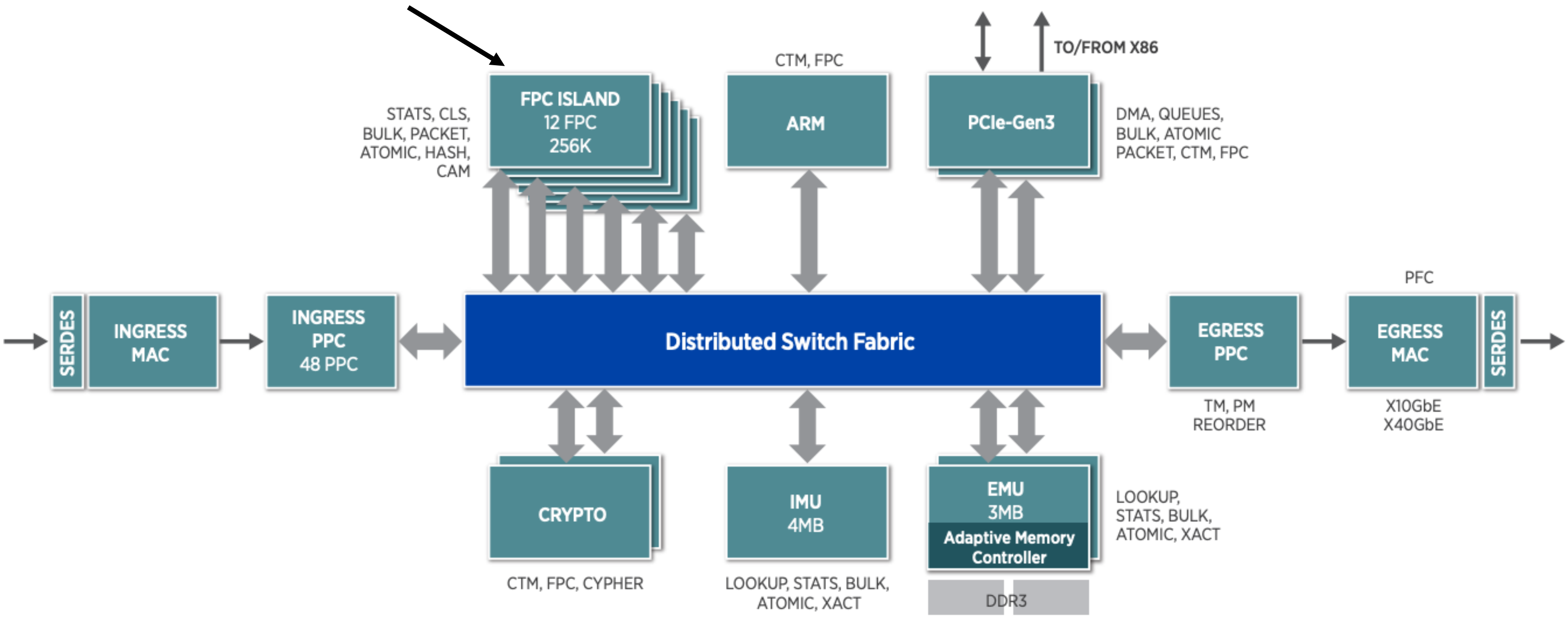


Key challenges

- SoC based SmartNICs have large number of wimpy cores with limited memories.
  - Parallel architecture geared towards stateless offloads.

- TCP connections require stateful sequential (in-order) processing.

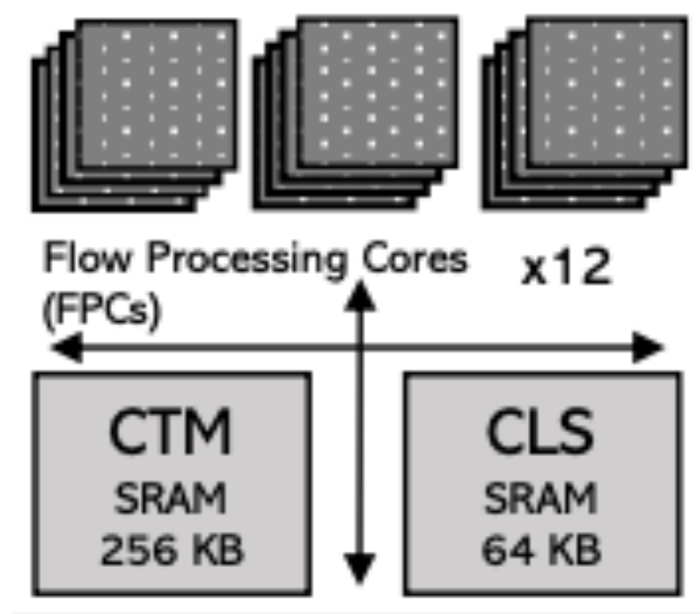
Netronome Agilio (NFP-4000)



Netronome Agilio (NFP-4000)

Each FPC island has 12 FPCs (flow processing cores).

- Each FPC is an independent 32 bit core at 800MHz.
- Each core supports up to 8 hardware threads.
- Lacks support for floating point operations or timers.



Small amount of memory.

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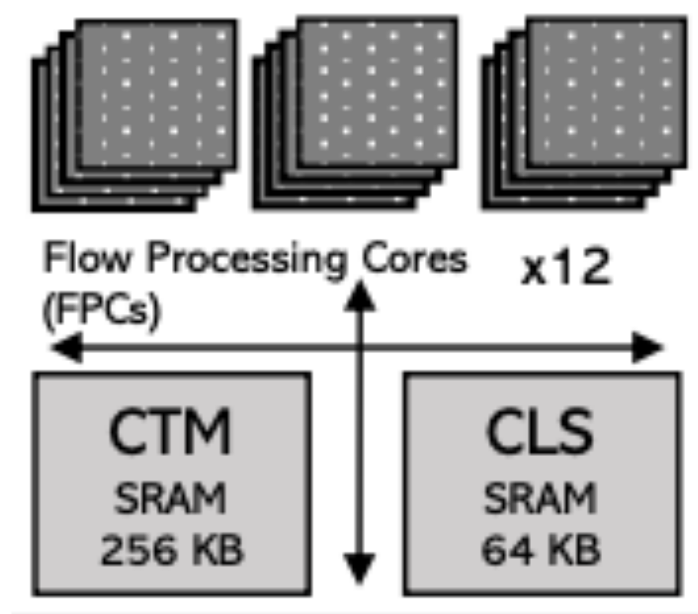
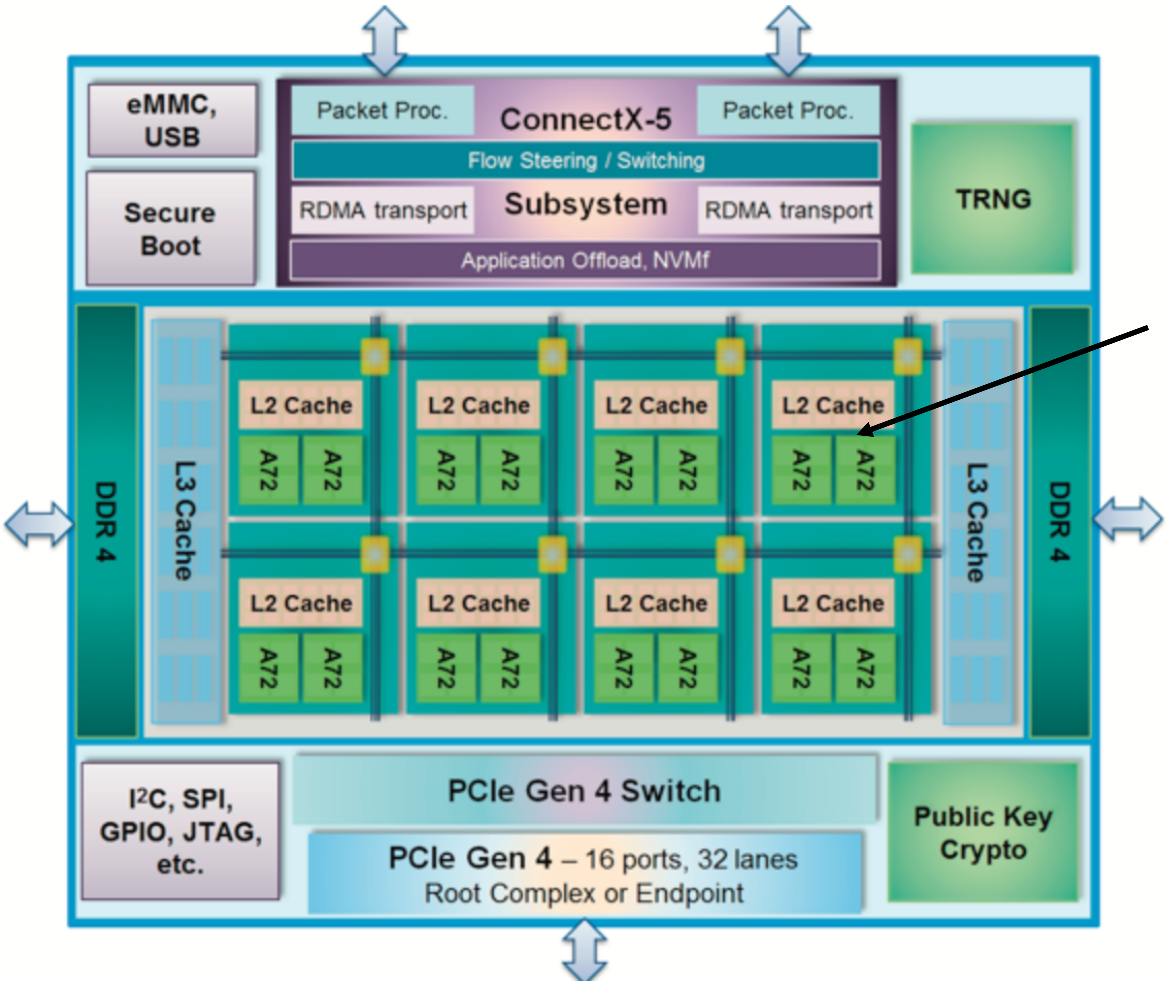


Small amount of memory.

NVIDIA (Mellanox) BlueField DPU



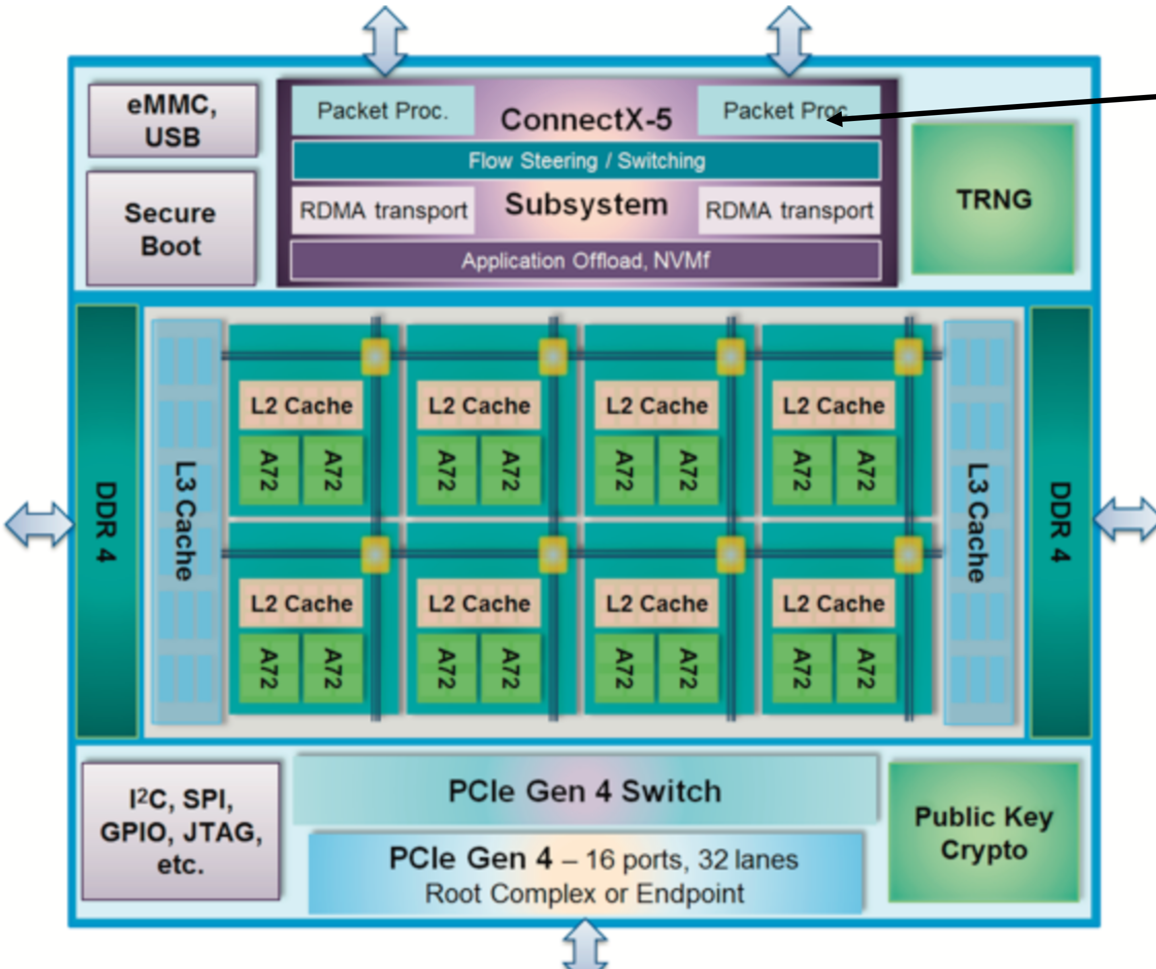
ARM cores

Bluefield DPU 2:
8 64bit cores
(upto 2GHz)

Bluefield DPU 3:
16 64bit cores
(upto 3GHz)
released in April 2021

Figure from: https://www.storagereview.com/news/nvidia-bluefield-2-dpu-delivers-record-setting-performance

NVIDIA (Mellanox) BlueField DPU



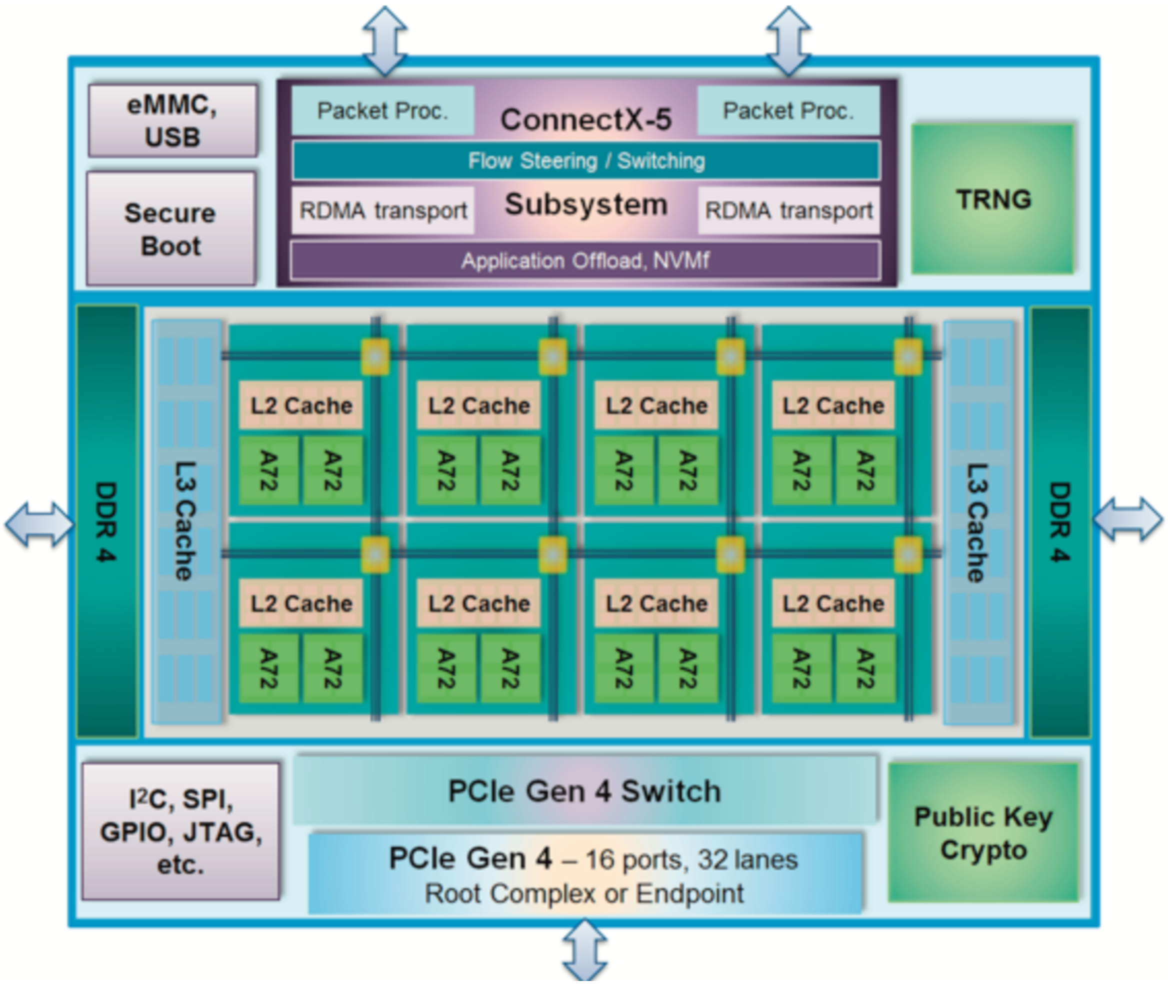
Programmable datapath accelerator

16 cores, 256 threads
for massive parallelism

Programmed through NVIDIA's DOCA interface.

Figure from: https://www.storagereview.com/news/nvidia-bluefield-2-dpu-delivers-record-setting-performance

NVIDIA (Mellanox) BlueField DPU



8MB L2 cache
16MB L3 cache

16GB on-baord RAM (DDR)

Figure from: https://www.storagereview.com/news/nvidia-bluefield-2-dpu-delivers-record-setting-performance

Key challenges

- SoC based SmartNICs have large number of wimpy cores with limited memories.
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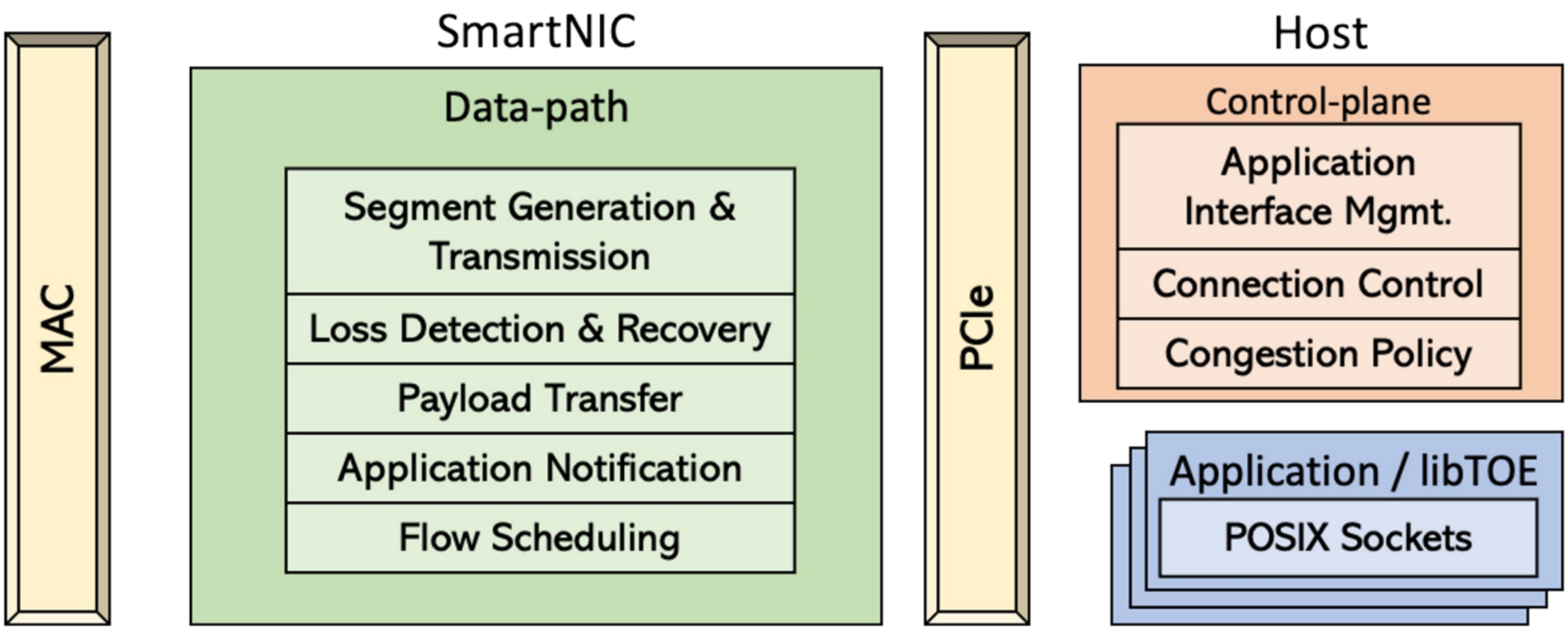
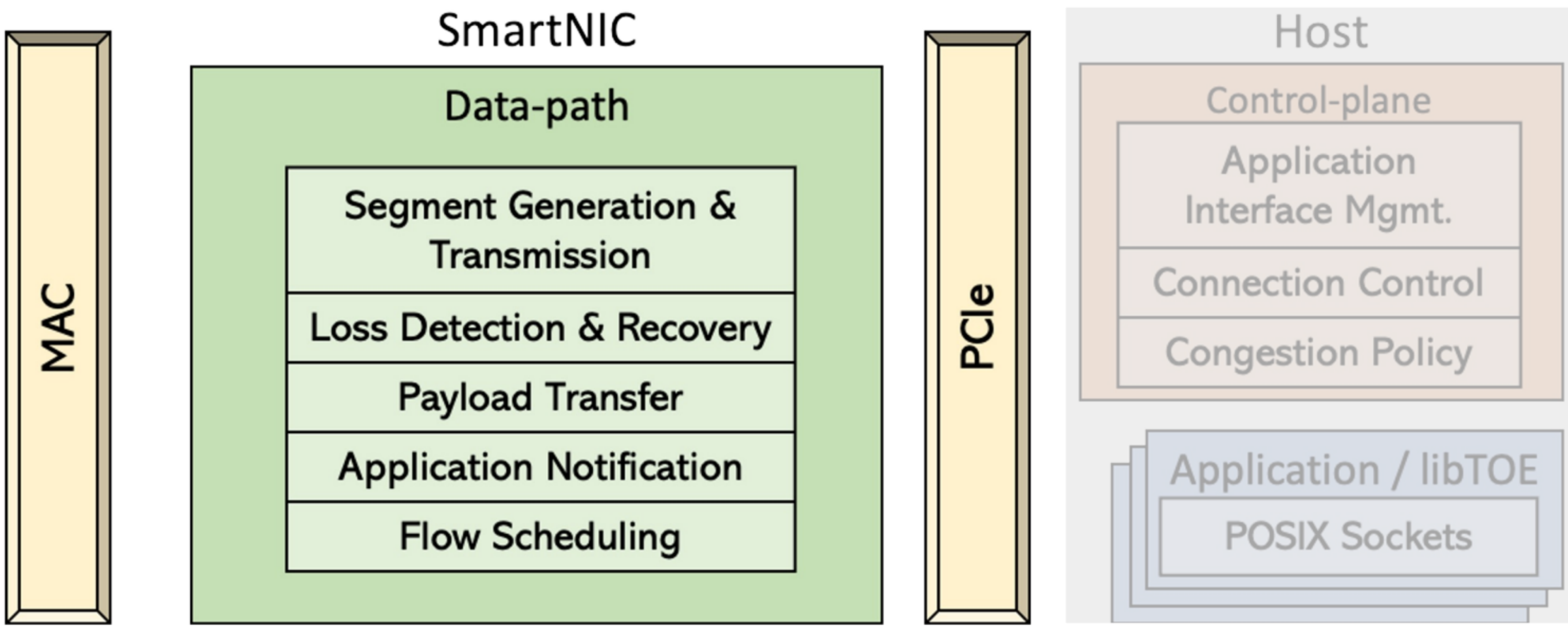
FlexTOE's approach

- Decouple control plane from datapath.
- Modularity: fine-grained modules keep private state and communicate explicitly
- Fine-grained parallelism: Modules may be replicated, sharded, execute out-of-order
- One-shot data-path offload: Payload is never buffered on the NIC

FlexTOE's Offload Architecture

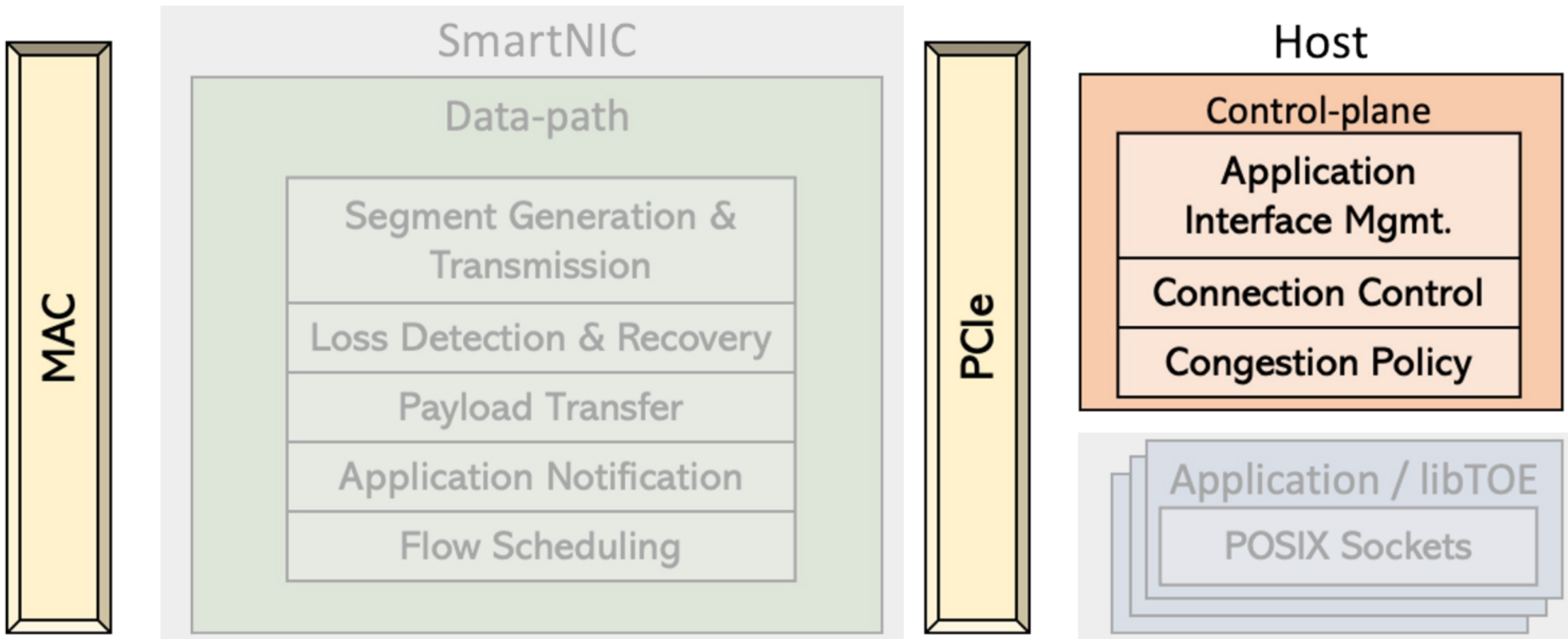


FlexTOE's Offload Architecture



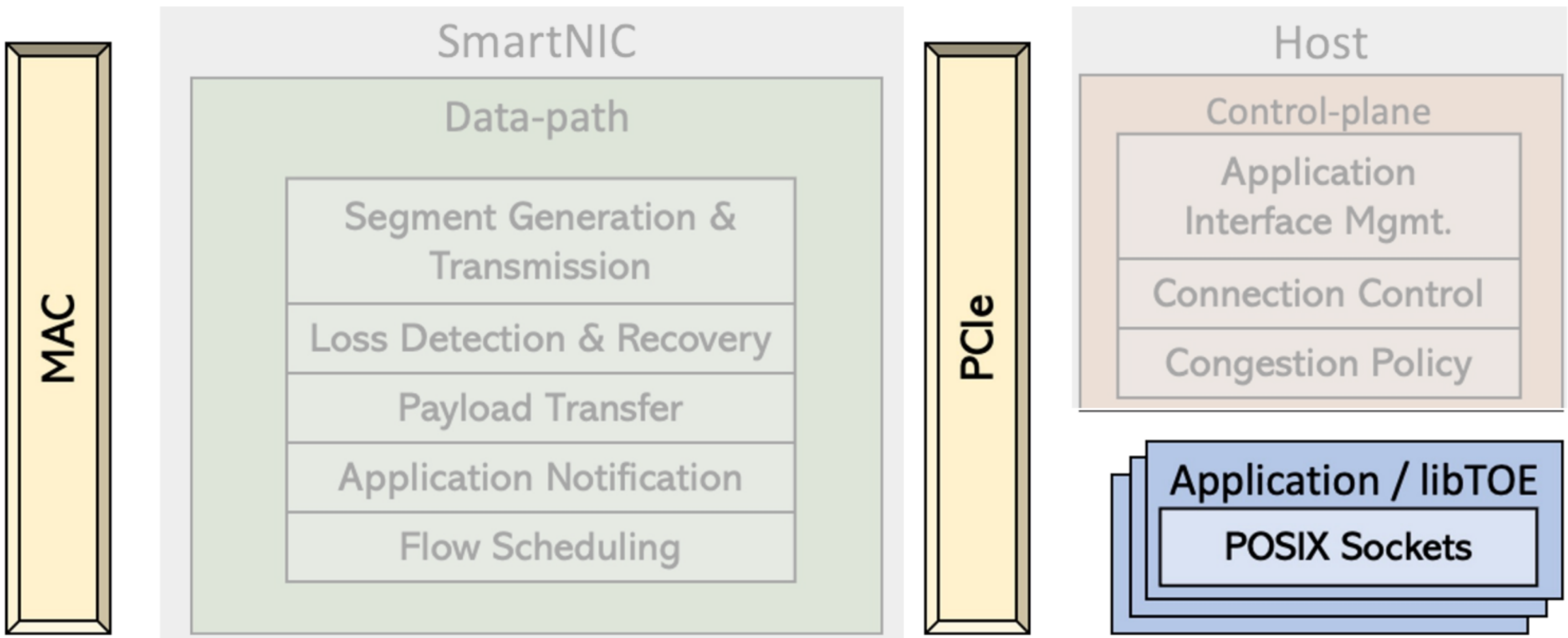
- **Data-path**: per-packet transport logic for established connections

FlexTOE's Offload Architecture



- **Control-plane:** policy, management and infrequent recovery code-paths

FlexTOE's Offload Architecture

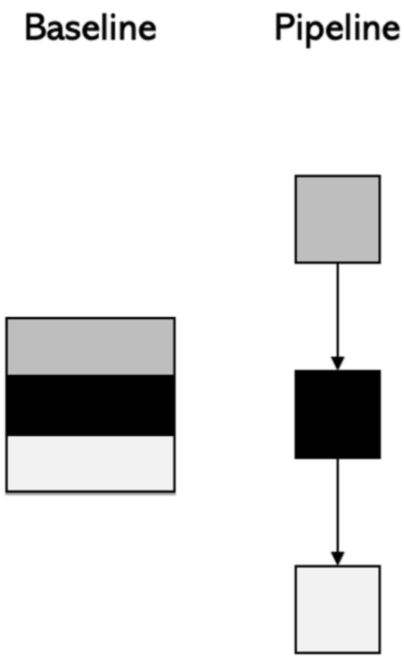


- **libTOE library:** provides POSIX sockets to the application with kernel-bypass

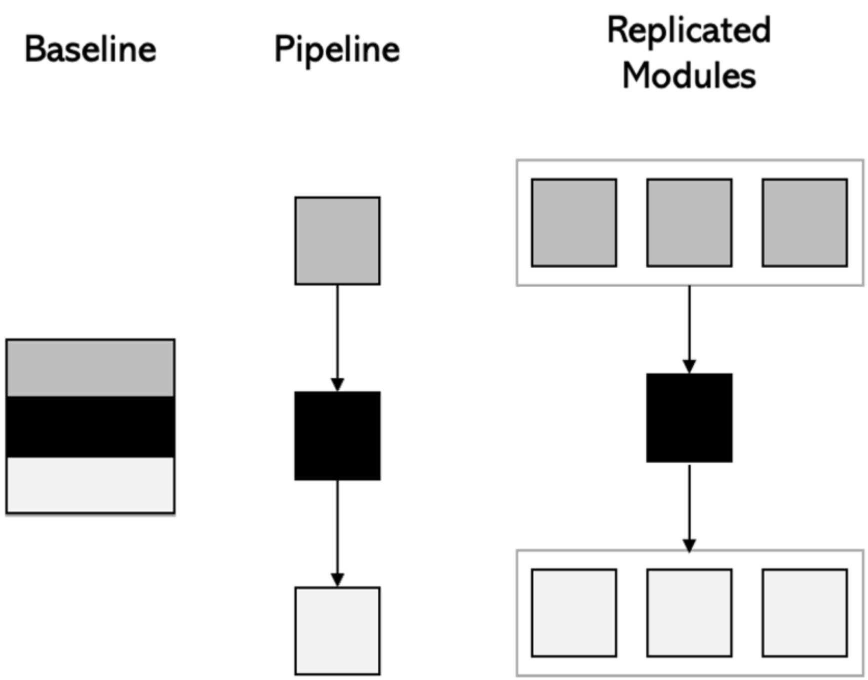
FlexTOE's on-NIC datapath

Baseline

FlexTOE's on-NIC datapath



FlexTOE's on-NIC datapath



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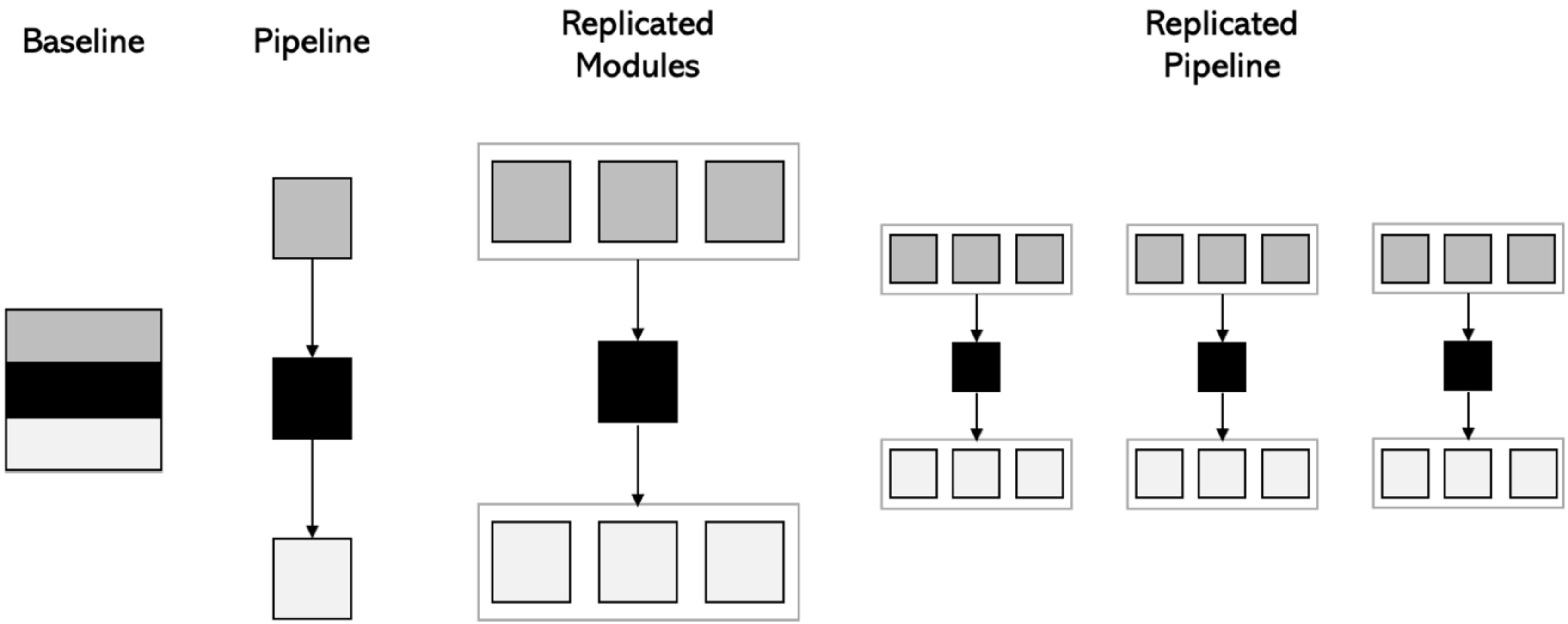
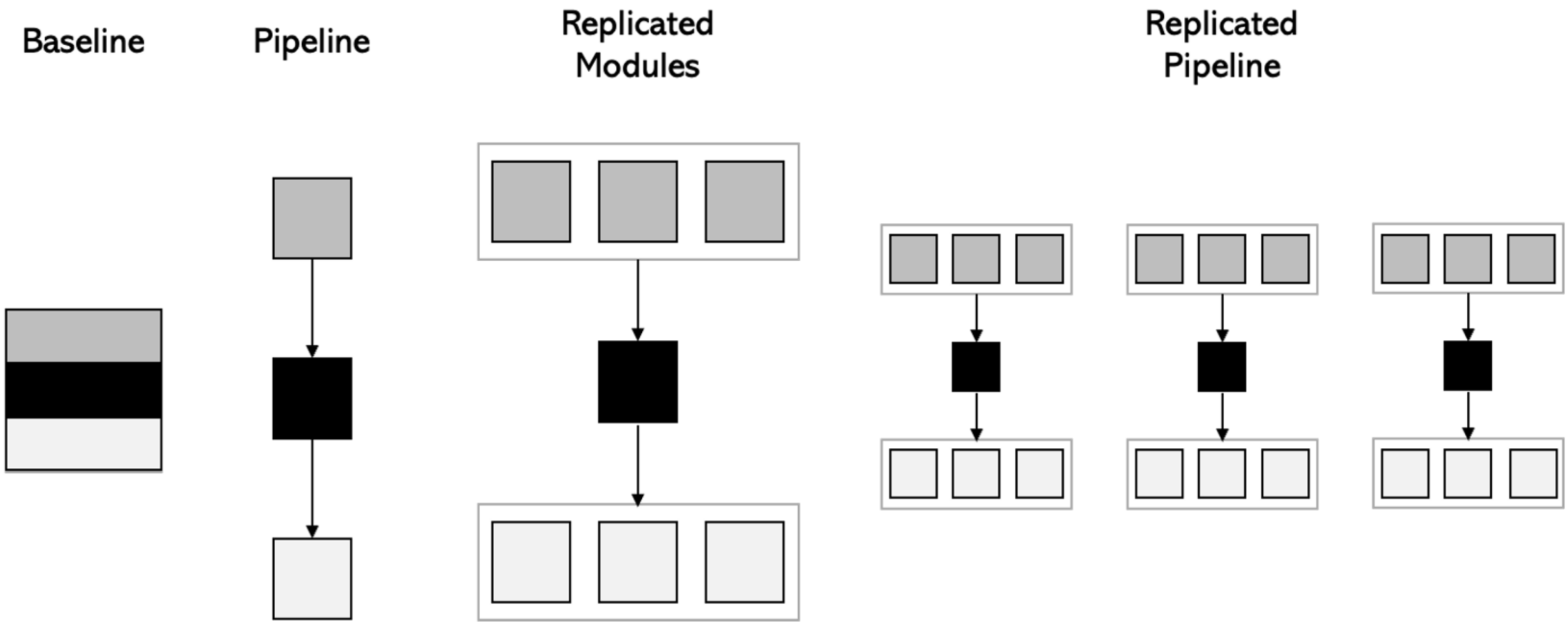
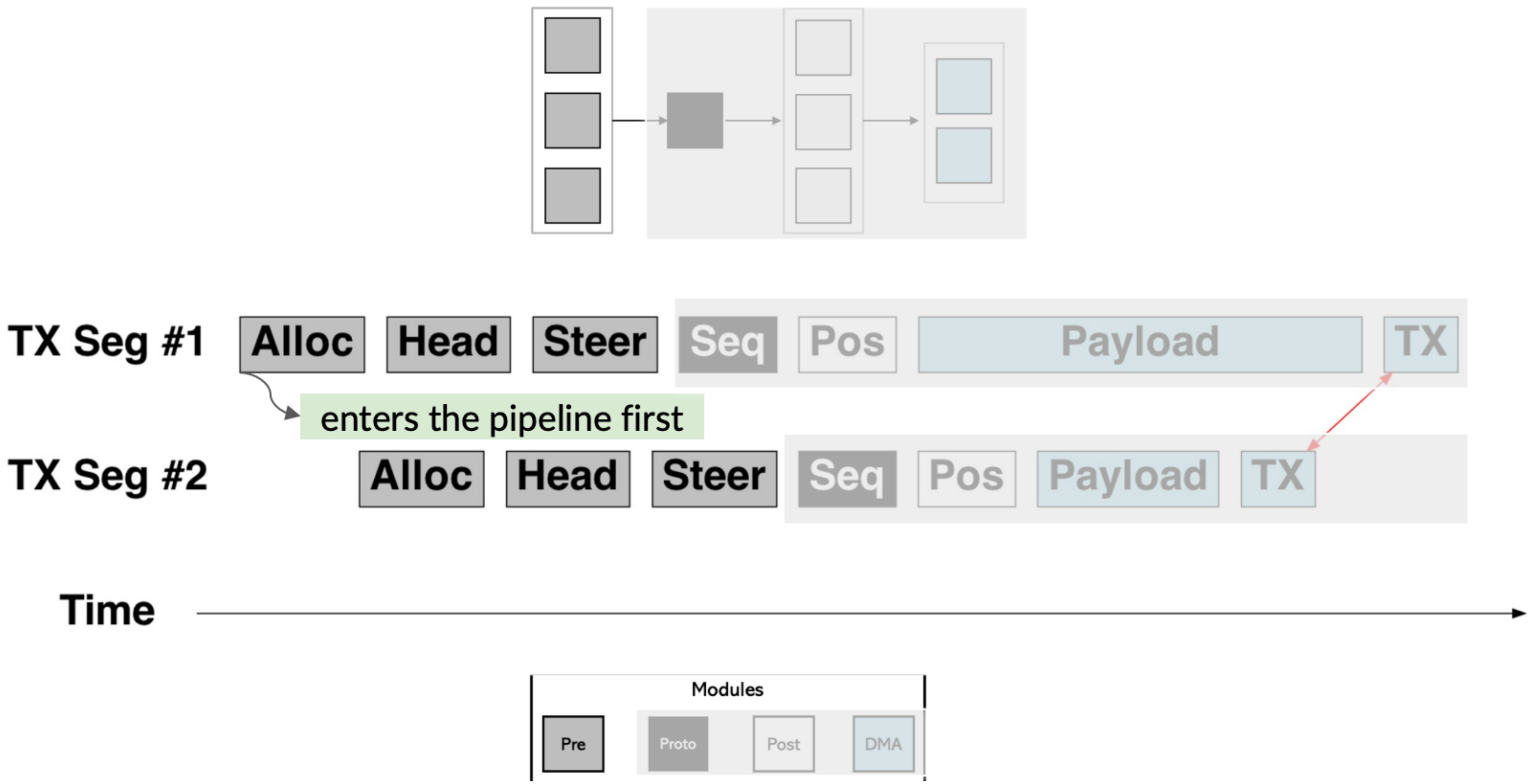


FlexTOE's on-NIC datapath



Example: Transmit (Tx)



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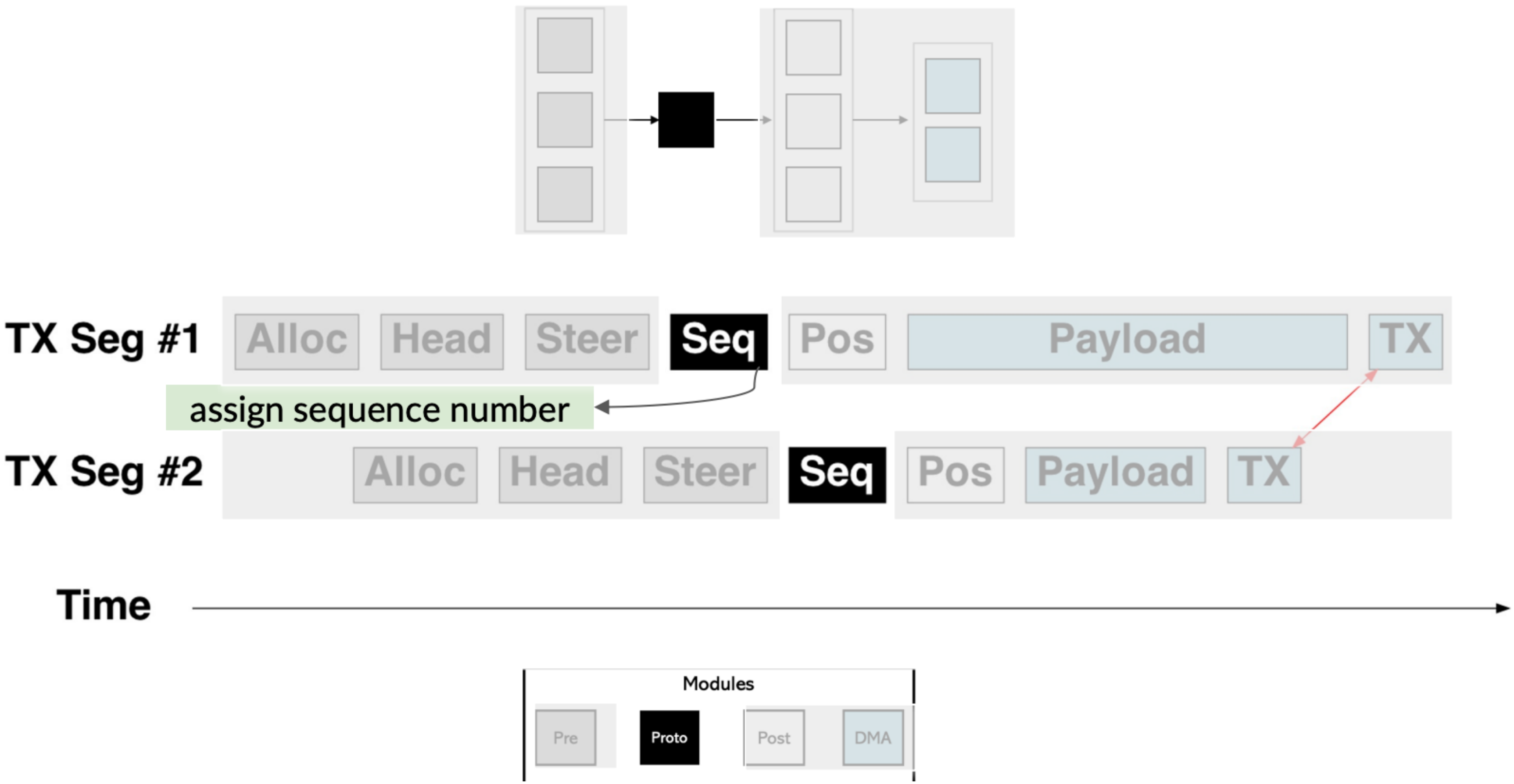
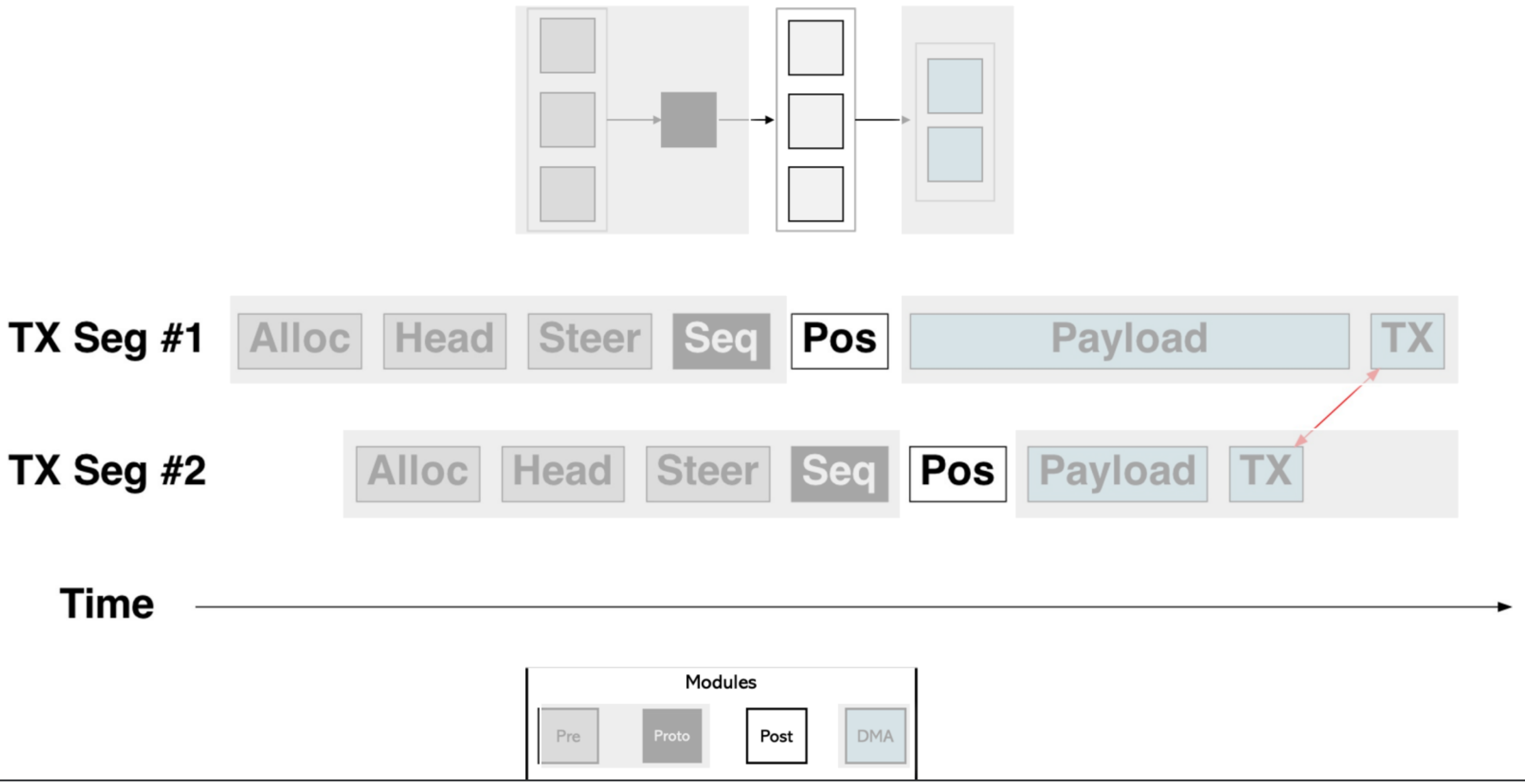
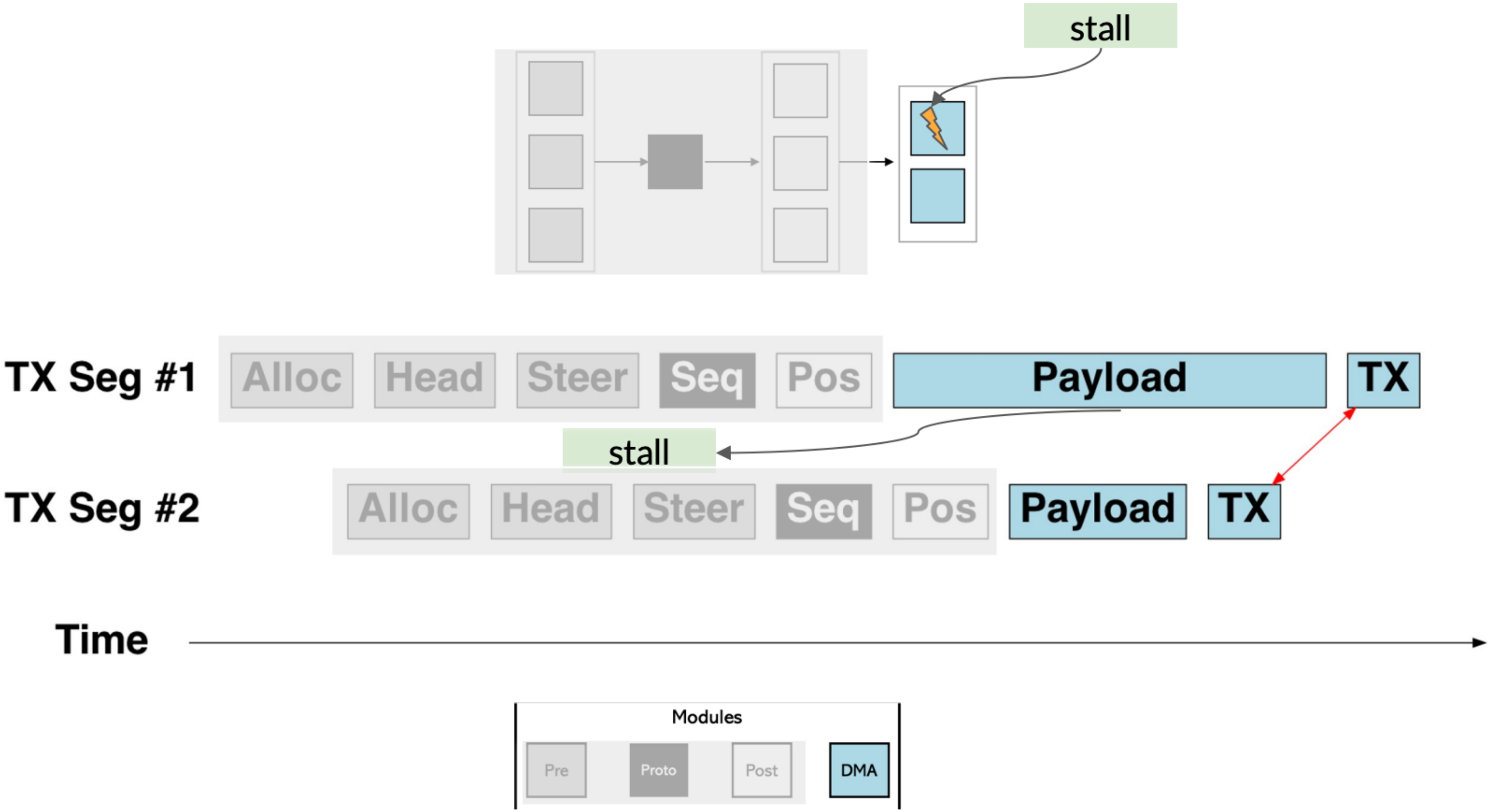


Example: Transmit (Tx)

Parallel TCP Processing Example: Transmit (TX)



Example: Transmit (Tx)

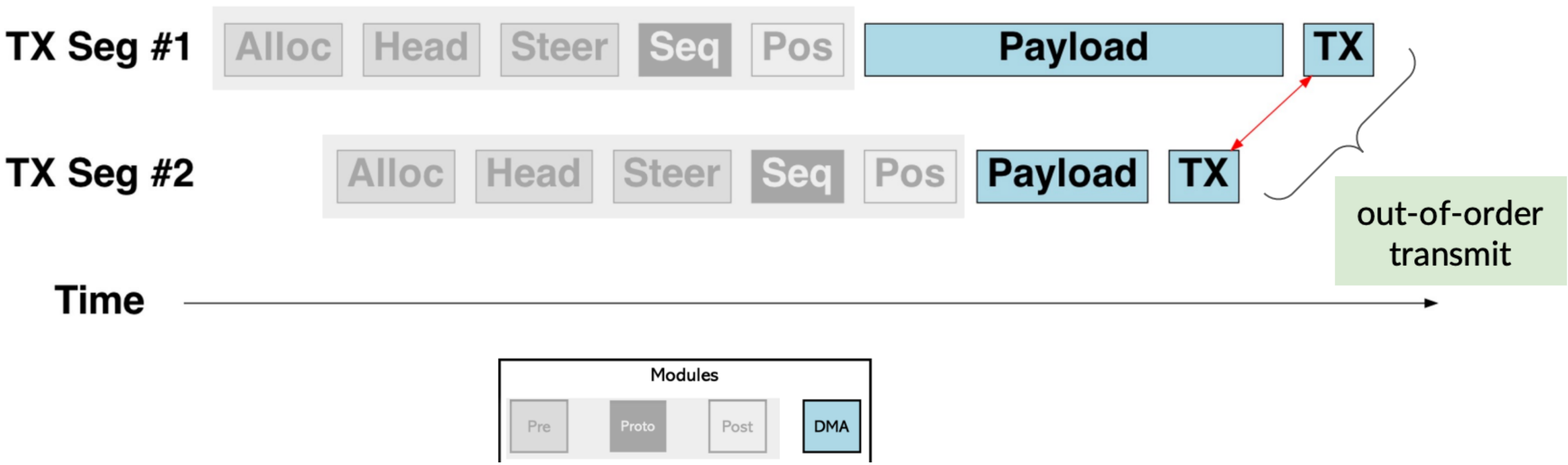


Example: Transmit (Tx)

TCP requires processing **in-order for loss detection**

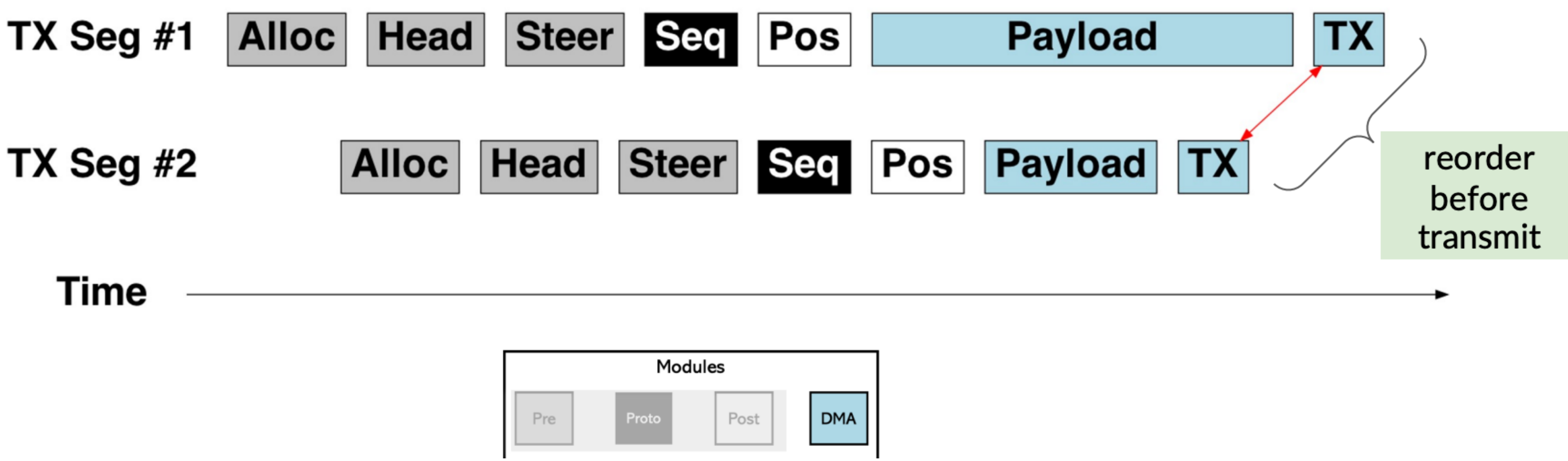
but …

Data-parallel modules have varying processing times and **may reorder segments**



Example: Transmit (Tx)

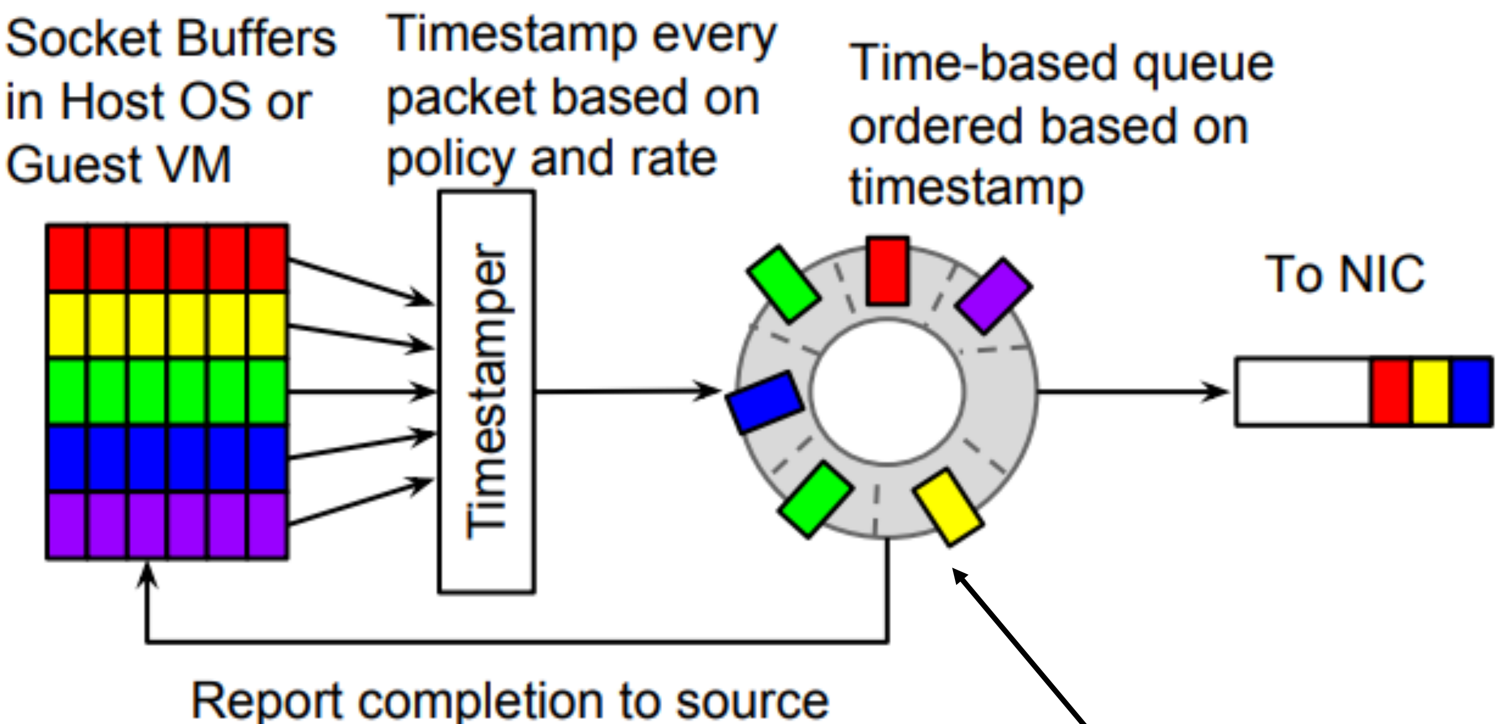
Assign sequence number on data-path ingress → reorder segments on egress



Other design and implementation aspects

- No buffering in NIC, but not zero-copy.
  - Send and receive buffers maintained in libTOE (POSIX-compliant).
- Transmissions triggered when app sends more data or when data is acked.
- On-NIC datapath takes care of retransmission due to duplicate acks.
- On-NIC datapath also generates acks (with ECN bits or timestamp information).
- On-NIC datapath collects relevant stats and reports them to on-host control plane (used for congestion control).
- On-host control plane handles rate/window adjustment (congestion control logic) and retransmissions due to timeouts.
- On-NIC datapath enforces per-flow rates using timing wheel (Carousel).
- Build specialized caches at different levels based NFP-4000's memory architecture.

Timing Wheel in Carousel



Time slots from "now" till "horizon".
All packets in the "now" slot get dequeued.
O(1) insertion and deletion.

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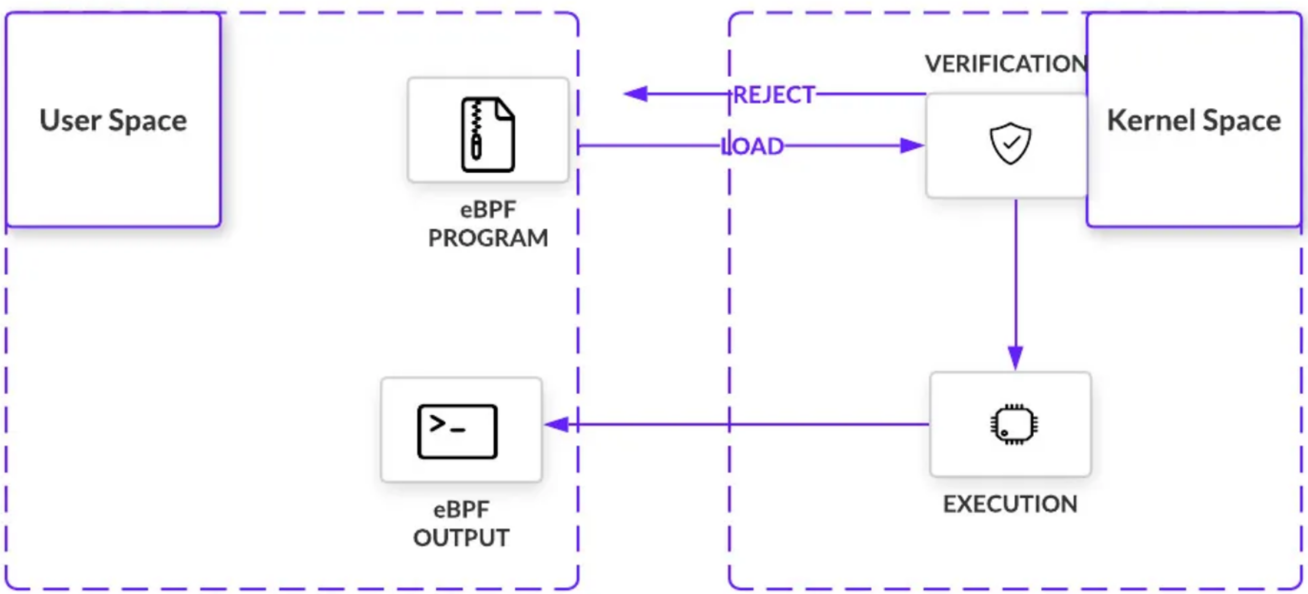
Enabling flexibility

- Support for XDP (eXpress Data Path) modules implemented in eBPF.

eBPF

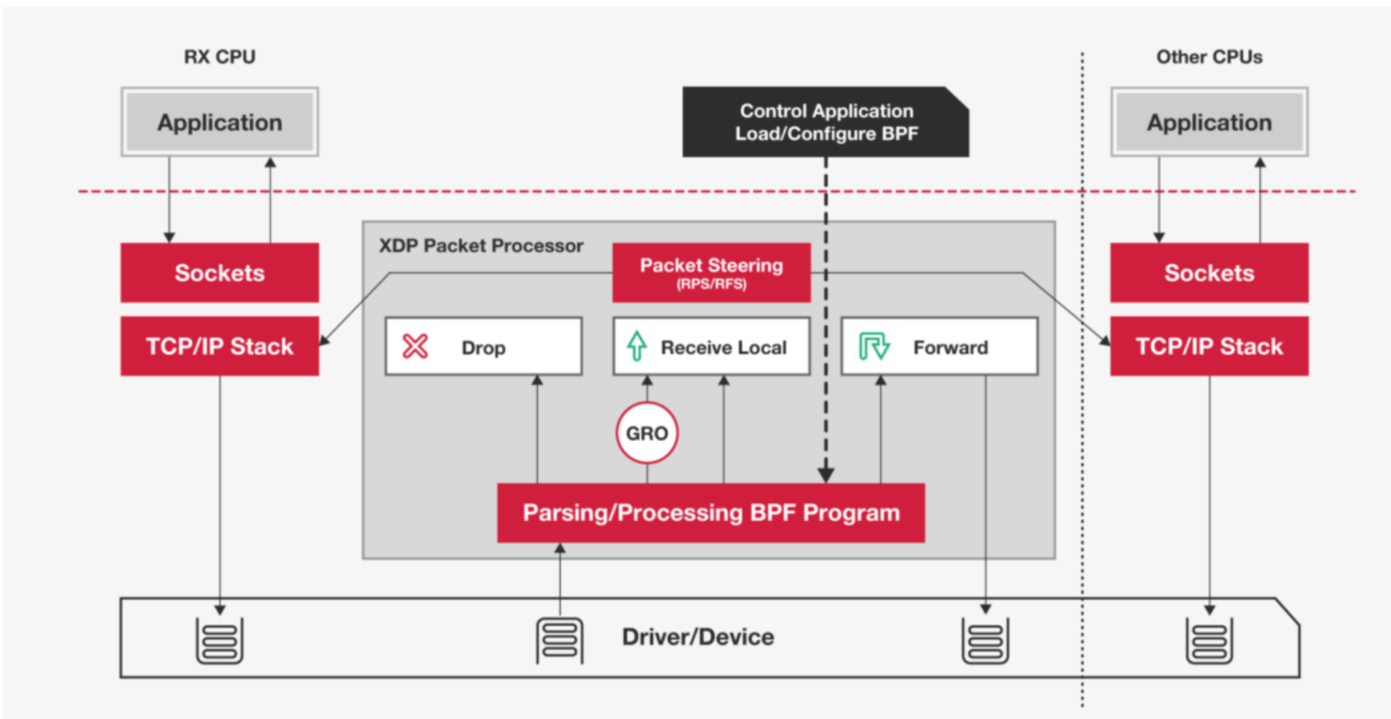
- Allows running verified code supplied by a user-space application in the kernel.
- eBPF programs are invoked when certain *hooks* are triggered (e.g. a system call, a network event, etc).



Source: https://www.infoq.com/articles/gentle-linux-ebpf-introduction/

XDP

- Uses eBPF to provide support for bare-metal processing of raw packets at the lowest point in the stack.



Source: https://www.iovisor.org/technology/xdp

Enabling flexibility

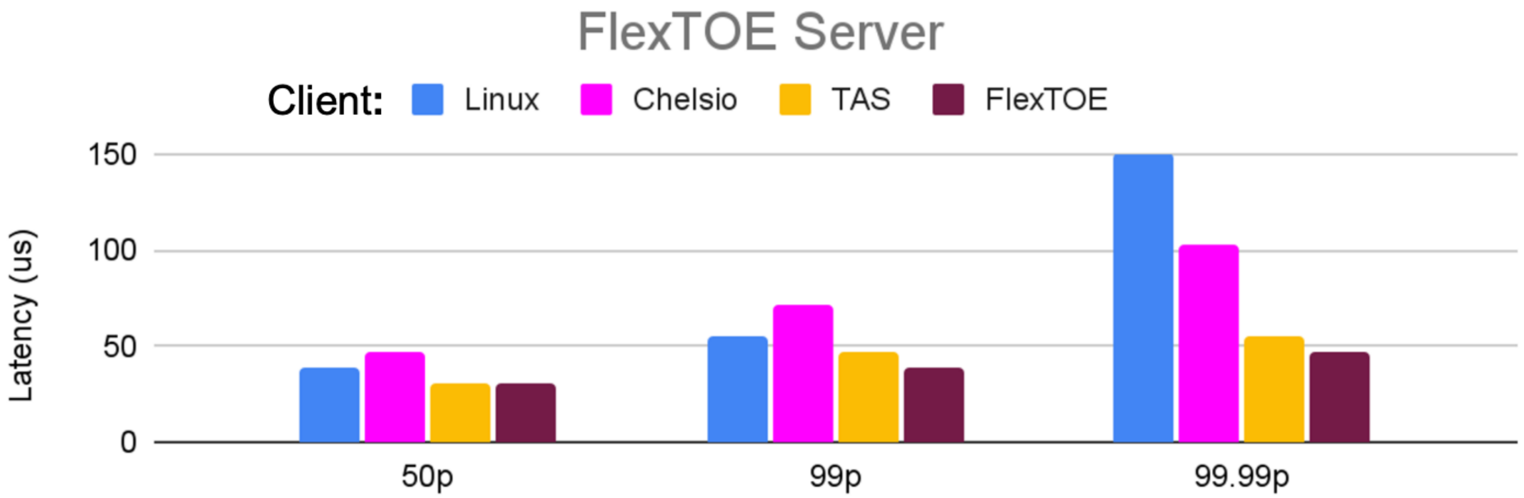
- Support for XDP (eXpress Data Path) modules implemented in eBPF.

- Use it to implement common datacenter features
  - Tracing, statistics, profiling
  - Connection firewalling
  - VLAN encapsulation/decapsulation
  - TCPDump.

Evaluation: tail latency

Memcached latency distribution across different stack combinations

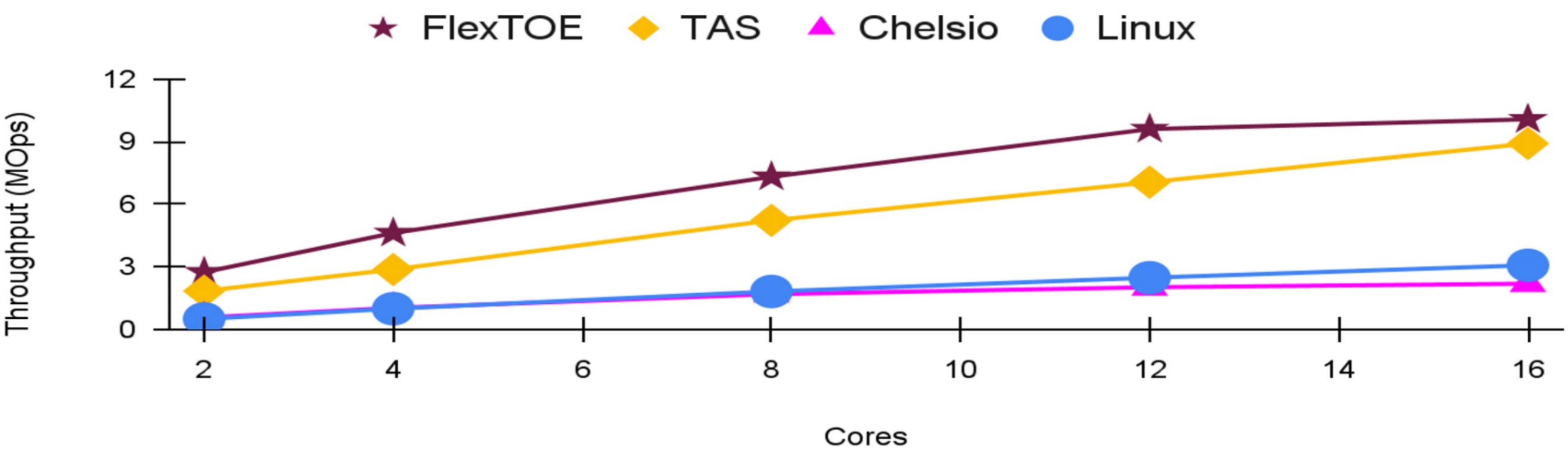
FlexTOE achieves the lowest median and tail latencies



Evaluation: throughput

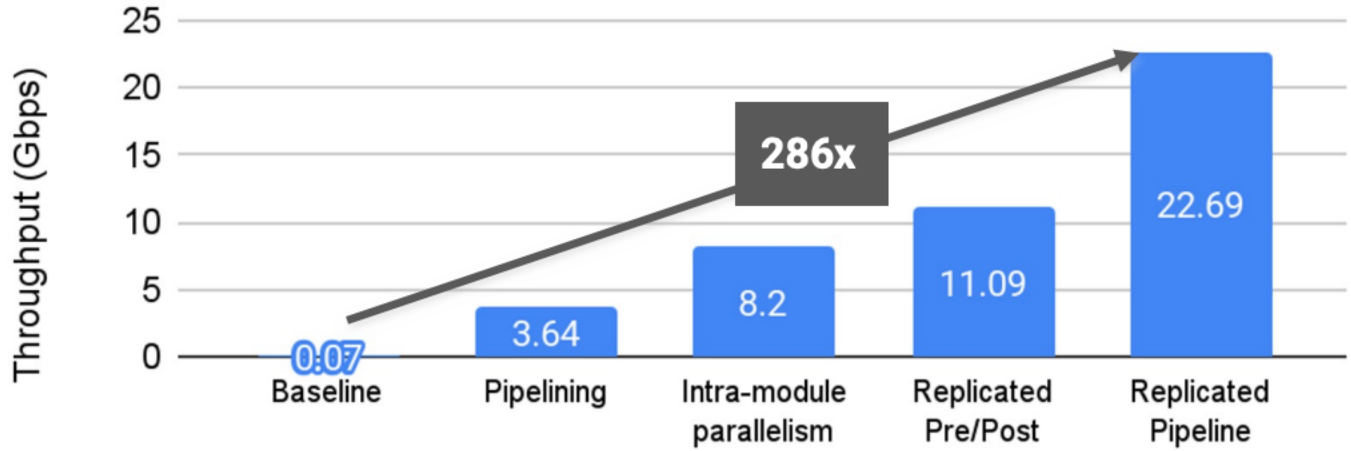
Memcached throughput, varying number of server cores

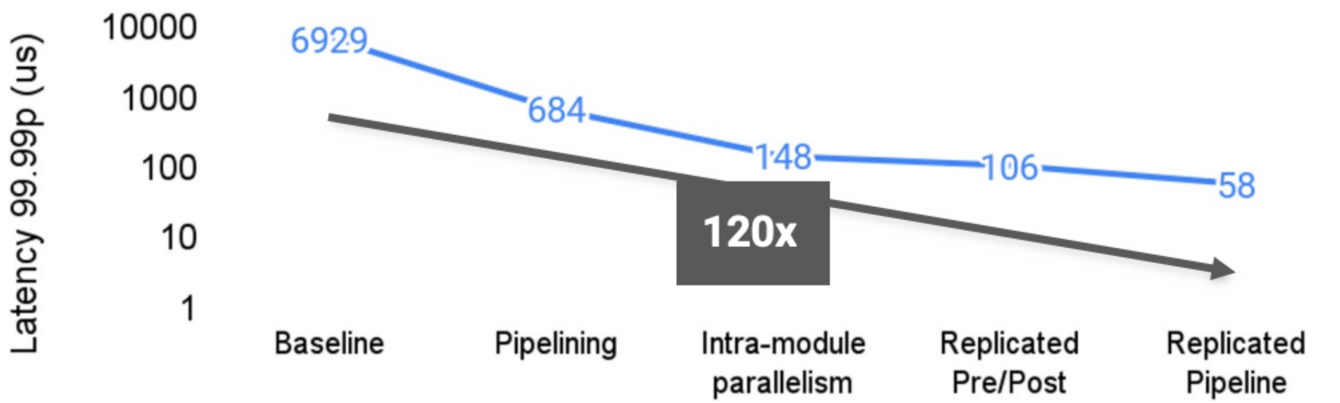
FlexTOE **saves up to 81% CPU cycles** versus Chelsio and **50%** versus TAS



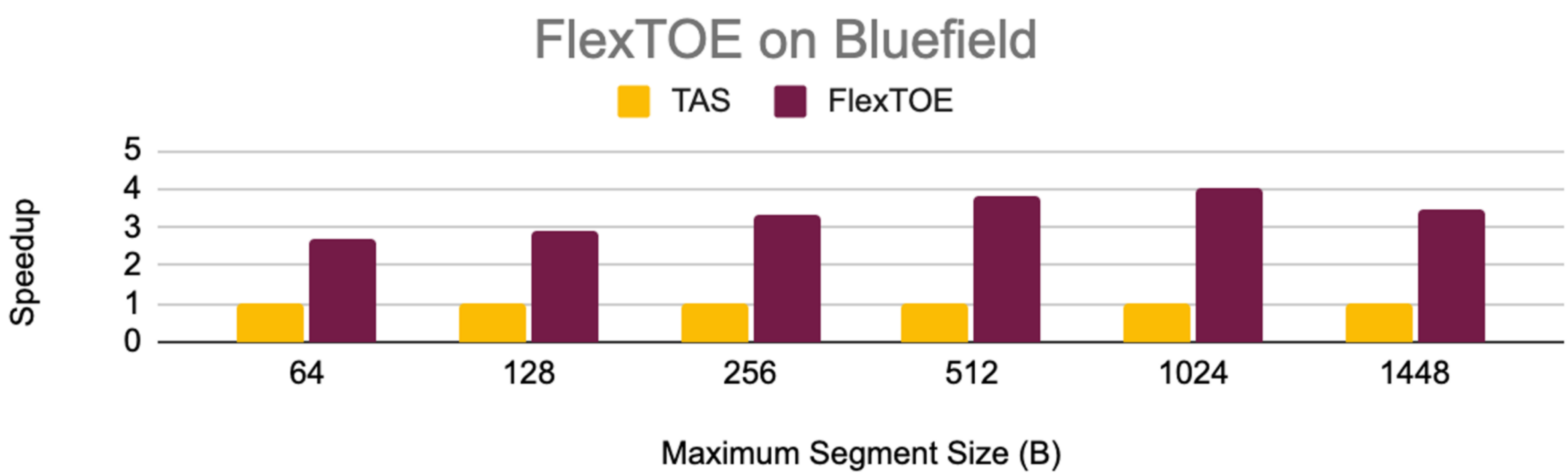
Even though latency difference is small between FlexTOE and TAS, why do we see a more significant throughput improvement?

Evaluation: factor analysis





Evaluation: on BlueField



Speedup = improvement in throughput

Your thoughts?

- What did you like about the paper?

- What were its limitations?

What are some other applications of smart NICs?

Other applications of SmartNICs

- Offloading distributed applications
  - iPipe, SIGCOMM'19
- Caching for key-value stores
  - IncBricks, ASPLOS'17
- Load balancing / request steering
  - RPCValet, ASPLOS'19
  - A Case for Informed Request Scheduling at the NIC, HotNets'19
- Remote memory calls, HotNets'20
- Network functions (using FPGA-based smartNICS)
  - ClickNP, SIGCOMM'16
  - FlowBlaze, NSDI'19
- …..